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EMISSIONS AND EFFICIENCY PERFORMANCE OF INDUSTRIAL COAL STOKER FIRED BOILERS

by

P. L. Langsjoen, J. O. Burlingame, and J. E. Gabrielson

KVB, INC.
6176 Olson Memorial Highway
Minneapolis, MN 55422

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Project Officers: R. E. Hall (EPA), W. T. Harvey and W. Siskind (DOE)

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The report gives results of field measurements of 18 coal stoker-fired boilers including spreader stokers, mass-fired overfeed stokers, and mass-fired underfeed stokers. The test variables included stoker design, heat release rate, excess air, coal analysis and sizing, overfire air, and flyash reinjection. Measurements included O2, CO2, CO, NO, NO2, SO2, SO3, gaseous hydrocarbons, uncontrolled and controlled particulate mass loading, particle size distribution of the flyash, combustible content of ash, sulfur retention in the ash, and boiler efficiency. Particulate loading is shown to be largely dependent on stoker type and degree of flyash reinjection. It increases with heat release rate, but can be controlled with proper use of overfire air in many cases. Nitric oxide increases with excess air and grate heat release rate. These relationships are defined in the report. Overfire air, as it exists in current boiler designs, does not affect NOx. The report also addresses other relationships between operating variables and measured emissions and efficiency. A separate data supplement is available.

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Combustion	Flue Gases	Combustion Modification	21B	
Coal	Fly Ash	Spreader Stokers	21D	
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R. D. Bessette	Island Creek Coal Sales Company
D. Clayton	Combustion Engineering, Inc.
T. Davis	Combustion Engineering, Inc.
N. H. Johnson	Detroit Stoker Company
W. E. Krauss	Cleaver Brooks Division
K. Luuri	Riley Stoker Corporation
K. J. McNamara	Riley Stoker Corporation
D. McCoy	E. Keeler Company
W. R. Murray	Foster Wheeler Limited
E. A. Nelson	Zurn Industries, Inc.
E. G. Poitras	The McBurney Corporation
P. E. Ralston	Babcock & Wilcox Company
D. C. Reschley	Detroit Stoker Company
R. A. Santos	Zurn Industries, Inc.
J. F. Wood	Babcock & Wilcox Company

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1.0 EXECUTIVE SUMMARY AND CONCLUSIONS

This report is the culmination of an extensive testing effort on eighteen coal-stoker fired boilers.[1-24] The effort includes 400 tests on 36 boiler-coal combinations conducted over a two year period. The boilers, identified by letter designators, fall into three major stoker classifications: spreader stokers (Sites A, B, C, E, F, G), mass fired overfeed stokers (Sites D, H, I, J, K, L2, L4), and underfeed stokers (Sites L1, L3, L5, L6, L7). Each of these classifications is presented separately in this report. The units are described in Table 1-1 along with the number of coals fired and tests conducted.

TABLE 1-1

UNIT DESCRIPTION AND DATA BASE

	Stoker Type	Design Capacity lb/hr	Number Coals Tested	Number Test Conditions
Site A	Spreader	300,000	3	68
Site B	Spreader	200,000	4	42
Site C	Spreader	182,500	3	76
Site D	Vibrating Grate	90,000	3	31
Site E	Spreader	180,000	3	25
Site F	Spreader	80,000	2	38
Site G	Spreader	75,000	3	35
Site H	Traveling Grate	45,000	1	24
Site I	Traveling Grate	70,000	2	23
Site J	Chain Grate	70,000	2	13
Site K	Traveling Grate	50,000	3	18
Site L1	Multiple Retort	26,000*	1	1
Site L2	Vibrating Grate	30,000	1	1
Site L3	Single Retort	23,300	1	1
Site L4	Traveling Grate	27,000	1	1
Site L5	Multiple Retort	28,460	1	1
Site L6	Multiple Retort	20,000	1	1
Site L7	Multiple Retort	50,000	1	1

*The Site L1-L7 report expresses steaming capacity in terms of peak, or maximum rating. This report expresses the Site L1-L7 steaming capacity in terms of maximum continuous ratings so as to be consistent throughout.

The major objective of this test program was to update stoker specification data. This was accomplished by measuring boiler emissions and efficiency on a variety of boiler-stoker designs and under a variety of operating conditions. The operating variables included heat release rate, excess air, overfire air, flyash reinjection and coal properties. The measurements included both uncontrolled and controlled particulate loading, nitrogen oxides (NO and NO_2), sulfur oxides (SO_2 and SO_3), oxygen (O_2), carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbons (HC), combustibles in the flyash and bottom ash, particle size distribution and boiler efficiency. The tests were conducted under steady load conditions.

In stoker firing of coal, there are so many variables that even with the extensive amount of testing conducted during this program it was not possible to analyze them all. The interactions between these variables are difficult to assess.

Not all of the parameters were determined on each site nor under the full range of operating variables. For example, the carbon monoxide analyzer was out-of-service during testing at Sites G, I and J. The hydrocarbon analyzer was only operable during testing at four sites, and boiler nameplate rating was not achieved on three of the units due to retrofit equipment on two units and startup problems on a third. In addition, the testing at Sites L1 through L7 was conducted under a separate contract and included a more limited number of test measurements under a single operating condition on each unit.

This summary is organized in two separate formats so as to be a convenient reference to the widest possible audience. The first section is organized by the measured parameter first and the operating variable second. Thus, for example, all observations on particulate loading are grouped together.

The second format follows the format of the text. It is organized by operating variable so that, for example, the effects of overfire air on all emissions are grouped together. As an additional convenience, each subject is cross referenced to the main body of the text.

The range of data encountered at full load are summarized in Table 1-2.

TABLE 1-2

RANGE OF DATA ENCOUNTERED AT HIGH LOAD*

	Spreader Stokers With Reinjection from D.C.**	Spreader Stokers W/O Reinjection from D.C.	Mass Fired Overfeed Stokers	Mass Fired Underfeed Stokers
Uncontrolled Particulate, lb/10^6Btu	12.7 - 36.4	2.1 - 8.8	0.57 - 2.2	0.25 - 0.71
Controlled Particulate, lb/10^6Btu	0.60 - 3.5	.17 - 3.8	0.11 - 0.75	0.46 - 0.58
Mechanical Collector Efficiency, %	94.9 - 98.0	40.6 - 96.0	10.9 - 92.7	26.6 - 42.9
Excess Air, %	18 - 113	19 - 82	26 - 97	33 - 186
Nitric Oxide, lb/10^6Btu as NO_2	.30 - .60	.36 - .61	.21 - .50	No Data
Carbon Monoxide, ppm dry @ 3% O_2	22 - 1600	33 - 702	39 - 2300	<1000
Unburned Hydrocarbons, ppm wet @ 3% O_2	No Data	0 - 41	5 - 112	No Data
Combustibles in Flyash, %	7.1 - 65.6	26.6 - 83.5	21.8 - 56.0	20.2 - 20.5
Combustibles in Bottom Ash, %	0.0 - 34.4	0.3 - 27.2	7.1 - 69.1	8.1 - 25.0
Flyash Combustibles Heat Loss, %	.54 - 5.5	.51 - 9.2	.16 - 1.1	.07 - .21
Bottom Ash Combustibles Heat Loss, %	.00 - 3.0	.04 - 3.4	.42 - 9.4	1.2 - 3.9
Boiler Efficiency, %	75.79 - 83.43	73.00 - 83.07	69.75 - 84.10	64.13 - 76.81

* Underfeed Stokers were Tested at Loads Ranging from 55-100% of Capacity. Data from the other Stokers were Obtained within the Upper 10% of the Obtainable Load Range.

** Does not Include Tests in which Reinjection from the Mechanical Collector was Reduced. For example, a nitric oxide level of .68 lb/10^6Btu as NO_2 measured during one reduced reinjection test is not included in this table. A particulate loading of 9.6 lb/10^6Btu is excluded for the same reason.

1.1 SUMMARY OF FINDINGS ORGANIZED BY MEASURED PARAMETER

PARTICULATE LOADING

- Type of Stoker

  Spreader stokers with flyash reinjection from their mechanical dust collectors had by far the highest uncontrolled particulate loadings, ranging from 13 to 36 lb/10^6Btu. Spreader stokers without reinjection from their dust collectors were next with emissions of 2.1 to 8.8 lb/10^6Btu, followed by mass fired overfeed stokers with .57 to 2.2 lb/10^6Btu and underfeed stokers with .25 to .71 lb/10^6 Btu. (Sections 3.2, 4.2, 5.4)

- Heat Release Rate

  It cannot be said that units with higher design heat release rates have higher particulate loadings, but for a given unit the uncontrolled particulate loading always increased as heat release rate, or load, increased. The rate of increase varied from site to site, and at some sites it appeared to accelerate as full load was approached. On spreader stokers with flyash reinjection from mechanical dust collectors, the last 10% increase in heat release rate resulted in a 9 to 20% increase in particulate loading. On spreaders without dust collector reinjection, the increase was 8 to 12%. On mass fired overfeed stokers, particulate loading increased anywhere from 3 to 20% as heat release rate was increased from 90 to 100% of design. (Sections 3.3.2, 4.3.2)

- Excess Air

  No relationship was established between particulate loading and excess air. This does not foreclose the existence of such a relationship, but rather indicates that such a relationship could not be deciphered from the data due to data scatter and uncontrolled variables. (Sections 3.4.1, 4.4.1)

- Overfire Air

  Uncontrolled particulate loading was reduced by 20 to 50% on four of six spreader stokers and three of five mass fired overfeed stokers when overfire air pressures were increased. Two sites showed the opposite trend and two sites were unaffected by changes in overfire air pressure. (Sections 3.6.1, 4.6.1)

- Coal Ash

  Coal ash could be related to particulate loading at only four of the ten test sites at which multiple coals were fired. On three of the spreader stokers it was established that particulate loading increased by .24 to .38 lb/10^6Btu for each one percent increase in coal ash. Stated in another way, if the coal ash is doubled at these sites, the particulate loading will increase by 15 to 30%. Thus, the relationship between coal ash and particulate loading was not one-to-one on these three units.

On one of the traveling grate stokers, a 4% ash washed coal and a 10% ash unwashed coal from the same mine were tested. The 250% increase in coal ash resulted in a 300% increase in particulate loading. In this case, the dramatic increase in particulate loading can be attributed to the type of ash, a clay like material in the surface of the coal, and to a corresponding increase in coal fines on the unwashed coal. (Sections 3.5.1, 4.5.1)

- Coal Fines

  Because of the movement of air through the grate and the upward movement of combustion gases through the furnace, the smallest coal and ash particles are carried out of the furnace by the gases rather than staying on the grate. This is called particle entrainment and is a problem from both a pollution and an efficiency standpoint. The liklihood of a particle being entrained is a function of its size and density, and the velocities in the furnace. The test data from this program showed a mathematical correlation between coal fines and particulate loading on five stokers. Particulate loading increased by .10 to .55 lb/10^6Btu whenever the percent of coal passing a 16 mesh screen increased by one percent. No correlation was found in studies of six other stokers. (Sections 3.5.1, 4.5.1)

- Flyash Reinjection

  Flyash from the dust collector was reinjected to the furnace of three of the six spreader stokers. In each case it was demonstrated that uncontrolled particulate loading was increased as a result of reentrainment of a portion of the reinjected ash. At one site, reinjection was completely eliminated for test purposes. As a result, uncontrolled particulate loading was reduced by 70 to 80% and controlled particulate loading was reduced by 40 to 50%. Reducing the degree of flyash reinjection reduced the percentage of larger particles in the flyash. This in turn reduced the mechanical dust collector efficiency. (Sections 3.7.4, 3.7.6)

- Emission Factors

  U.S. Environmental Protection Agency publication AP-42, Compilation of Air Pollutant Emission Factors, Third Edition, contains factors used for predicting emissions from stoker-boilers. The data from this program compares as follows: (Sections 3.2, 4.2, 5.4)

	Uncontrolled Particulates, lb/ton (A = % Ash in Coal)	
	AP-42	This Program
Spreaders with Reinjection	20A	29A - 50A
Spreaders without Reinjection	13A	14A - 17A
Overfeed Stokers	5A	1.1A - 3.8A
Underfeed Stokers	5A	.6A - 1.7A

- Particle Size Distribution

  Particle size distribution of the flyash was determined by a variety of methods including cascade impactor, Bahco classifier, SASS cyclones and sieve analysis. The results varied from one method of measurement to another, but clearly showed that spreader stokers emit a higher percentage of coarse, more easily collected particles than mass fired overfeed and underfeed stokers. (Sections 3.8, 4.7, 5.7)

NITRIC OXIDE

- Type of Stoker

  As a class, spreader stokers emitted higher concentrations of nitric oxide than did mass fired overfeed stokers. Under full load conditions, spreader stokers emitted between .30 and .61 lb/10^6Btu NOx corrected to NO_2 while mass fired overfeed stokers emitted between .21 and .50 lb/10^6Btu NOx. However, overfeed stokers operated at higher excess air levels than did spreader stokers. When compared at the same excess air levels the difference in NOx levels is even greater. However, mass fired overfeed stokers generally require higher excess air than spreader stokers. (Sections 3.2, 4.2)

- Heat Release Rate

  For spreader stokers, an increase in heat release rate equivalent to 10% of capacity resulted in an average increase in nitric oxide emissions of .025 lb/10^6Btu as NO_2 at constant excess air. For mass fired overfeed stokers, the relationship ranged from zero to .026 lb/10^6Btu per 10% increase in capacity at constant excess air. In all cases, nitric oxide emissions were invarient with load at normal firing conditions because the effects of decreasing excess air effectively canceled the effects of increasing load. Although NOx increased with heat release rate on each given unit, it was not true that units with higher design heat release rates emitted higher concentrations of NOx. (Sections 3.3.5, 4.3.5)

- Excess Air

  On four spreader stokers without air preheat and one with air preheat, nitric oxide increased by .021 to .036 lb/10^6Btu for each increase of 10% excess air. The sixth spreader stoker used air preheat and its NOx increased by .067 lb/10^6Btu per increase of 10% excess air. On five mass fired overfeed stokers, NOx increased by .016 to .027 lb/10^6Btu. (Sections 3.4.3, 4.4.3)

- Overfire Air

  Nitric oxide emissions were not influenced by changes in overfire air pressure when considered at constant excess air. (Sections 3.6.3, 4.6.3)

- Fuel Nitrogen

  Variations in fuel nitrogen from .75% to 1.50% by weight had no measurable effect on nitric oxide emissions. This may simply reflect difficulties in sorting out the other variables. (Section 3.5.4, 4.5.4)

- Flyash Reinjection

  Flyash reinjection from the mechanical dust collector had no measurable effect on nitric oxide emissions. (Section 3.7)

- Emission Factors

  U.S. Environmental Protection Agency publication AP-42, Compilation of Air Pollutant Emission Factors, Third Edition, contains factors used for predicting emissions from stoker boilers. The data from this program compares as follows: (Sections 3.2, 4.2)

	Nitrogen Oxides, lb/ton	
	AP-42	This Program
Spreader Stokers	15	9.4 - 14.2
Overfeed Stokers	None	7.1 - 9.4

SULFUR OXIDES

- Type of Stoker

  The spreader stokers retained an average 4.4 percent of the fuel sulfur in the ash, while the mass fired overfeed stokers retained an average 2.1 percent. The remainder was emitted as SO_2 and SO_3, with SO_3 comprising less than two percent of the total. Operating parameters such as excess air, overfire air, and load had no effect on the emissions of sulfur oxides or the retention of sulfur in the ash.

- Fuel Sulfur

  Although good sulfur balances were difficult to obtain, the data indicates that fuel sulfur conversion efficiencies of 95 to 98% are reasonable assumptions. (Sections 3.5.3, 4.5.3)

CARBON MONOXIDE

- Type of Stoker

  Spreader stokers emitted lower concentrations of carbon monoxide than traveling grate stokers while firing Eastern bituminous coals. Emissions from three of the spreader stokers were in the range of 50 to 250 ppm at full load. A fourth was in the range of 200 to 600 ppm. By comparison, two traveling grate stokers emitted 50 to 700 ppm CO at full load, and a vibrating grate stoker emitted between 50 and 2000+ ppm CO. The comparison is limited to these seven stokers. Carbon monoxide emissions were not measured on three other stokers due to instrument failure, and a fourth fired only Western coals. At Test Sites L1 through L7, the carbon monoxide concentration was measured with an Orsat analyzer having a minimum detection limit of 0.1% or 1000 ppm. Significantly, the carbon monoxide emissions were below this detection limit on the Site L stokers. (Sections 3.2, 4.2)

- Heat Release Rate

  Carbon monoxide emissions were highest at high heat release rates under low excess air conditions, and at low heat release rates under high excess air conditions. At full load, carbon monoxide emissions could be controlled with proper application of combustion air. (Sections 3.3.6, 4.3.6)

- Excess Air

  Carbon monoxide was more prevalent as excess air dropped below about 30-40% on spreader stokers and about 60% on mass fired overfeed stokers. Carbon monoxide increased gradually as excess air increased above about 60% on spreader stokers and 100% on mass fired overfeed stokers. (Sections 3.4.4, 4.4.4)

- Overfire Air

  Carbon monoxide emissions were reduced by the increased use of overfire air. (Sections 3.6.4, 4.6.4)

- Coal Rank

  Carbon monoxide emissions were greatest while firing Western subbituminous coals. On one spreader stoker where both an Eastern and a Western coal were fired, the full load Western coal emissions ranged from 163 to 702 ppm and averaged 342 ppm. By comparison, the full load Eastern coal emissions ranged from 33 to 263 ppm and averaged 71 ppm. (Sections 3.5.5, 4.5.5)

- Flyash Reinjection

  Flyash reinjection from the mechanical dust collector had no measurable effect upon carbon monoxide emissions. (Section 3.7)

UNBURNED HYDROCARBON

- Type of Stoker

  Based on limited data, the spreader stokers emitted lower hydrocarbon emissions than the mass fired overfeed stokers. Full load emissions from the spreader stokers ranged from 0 to 15 ppm for Site F and 35 to 41 ppm for Site G. By comparison, the mass fired overfeed stokers emitted between 5 and 112 ppm for Site H and 80 ppm for a single point on Site J. (Sections 3.2, 4.2)

- Heat Release Rate

  Unburned hydrocarbons tended to decrease as heat release rate increased on three of four stokers where this emission was measured. On the fourth stoker, the opposite trend was observed. (Sections 3.3.4, 4.3.7)

- Excess Air

  Unburned hydrocarbon emissions showed little or no correlation with excess air on spreader stokers. On mass fired overfeed stokers, hydrocarbons increased in almost direct proportion to the excess air. (Sections 3.4.5, 4.4.5)

- Overfire Air

  Unburned hydrocarbons were reduced 82% by increasing the overfire air pressure on one traveling grate stoker. No correlation was found on one spreader stoker. The other two units where hydrocarbon emissions were measured had insufficient data to make a correlation. (Sections 3.6.5, 4.6.5)

- Coal Properties

  The site firing the lower volatile coal had the lowest hydrocarbon emissions. The 29% volatile coal yielded 19-41 ppm hydrocarbons while the 41% volatile coal yielded 163 to 702 ppm hydrocarbons. Volatiles are expressed here on a dry, mineral matter free basis. (Sections 3.5.6, 4.5.6)

- Carbon Monoxide

  Unburned hydrocarbons increased with increasing carbon monoxide emissions on one traveling grate stoker. No correlation was found on one spreader stoker. (Section 4.4.5)

EXCESS AIR

- Type of Stoker

  At full load, most spreader stokers were capable of operating at 30% excess air (5% O_2). By comparison, the mass fired overfeed stokers generally required 50% excess air (7% O_2). (Sections 3.2, 4.2)

- Size of Stoker

  With one exception, the excess air operating level was inversely proportional to the size of the stoker. The larger the stoker, the lower the excess air requirement. (Sections 3.3.1, 4.3.1)

- Heat Release Rate

  The excess air requirement drops as heat release rate increases on stoker boilers. The excess air requirement levels off as 30% excess air is approached. (Sections 3.3.1, 4.3.1)

- Coal Properties

  Coal properties were not found to alter excess air requirements on these stoker boilers.

COMBUSTIBLES IN THE BOTTOM ASH

- Type of Stoker

  Combustible levels were lower in the bottom ash of spreader stokers than they were for mass fired overfeed stokers or underfeed stokers. The average for each of six spreader stokers fired at full load ranged from 0% to 14%. By comparison, mass fired overfeed stokers ranged from 16% to 26% with one unit averaging 43%, and underfeed stokers ranged from 19 to 25% with one unit averaging 8%. (Sections 3.2, 4.2, 5.5)

- Heat Release Rate

  Heat release rate had very little effect on combustibles in the bottom ash. (Sections 3.3.4, 4.3.4)

- Excess Air

  No correlation was found between excess air and combustibles in the bottom ash. (Sections 3.4.2, 4.4.2)

- Coal Properties

  Small differences in bottom ash combustible levels were observed which appeared to be related to coal properties at some sites. However, the particular coal properties causing these differences were not identified. (Sections 3.5.2, 4.5.2)

- Ash Balance

  It was found that 65% to 85% of the coal ash remained on the grate in spreader stokers as compared to 80% to 90% for mass fired overfeed stokers. For the purposes of computing combustible heat losses, 75% and 85% are good estimates for spreaders and mass fired overfeed stokers, respectively. (Sections 3.5.2, 4.5.2)

COMBUSTIBLES IN THE FLYASH

- Type of Stoker

  Combustible levels in the flyash were higher in the spreader stokers than in either the mass fired overfeed stokers or the underfeed stokers. With the exception of Test Site C, the spreader stoker data ranged from 47% to 84% and averaged 60%. On the other hand, the mass fired overfeed stoker data ranged from 22% to 56% and averaged 28%. Flyash samples taken from the dust collector hoppers of two underfeed stokers revealed 20.2% and 20.5% combustibles. (Sections 3.2, 4.2, 5.5)

- Heat Release Rate

  Combustibles in the flyash tended to increase slightly as heat release rate increased on spreader stokers. On mass fired overfeed stokers, no significant trend was observed. (Sections 3.3.3, 4.3.3)

- Excess Air

  No correlation was found between combustibles in the flyash and excess air level on either spreader stokers or mass fired overfeed stokers. (Sections 3.4.2, 4.4.2)

- Overfire Air

  Increasing overfire air pressure effectively reduced the combustible content of the flyash by an average 40% in 74% of the overfire air tests. This resulted in an average efficiency gain of 1.70% of heat input for spreader stokers and 0.27% of heat input for the mass fired overfeed stokers. 26% of the tests gave the opposite result. (Sections 3.6.2, 4.6.2)

- Coal Properties

  At Test Site C, the combustibles in the flyash were 2 to 4 times higher while firing an Eastern bituminous coal than while firing a Western sub-bituminous coal. This was the only site where flyash combustibles could be directly related to coal properties. The particular property of the coal responsible for the difference was not identified. (Sections 3.5.2, 4.5.2)

- Flyash Reinjection

  Combustibles in the flyash at the boiler outlet increased by 23% to 63% when the rate of flyash reinjection was reduced. At the dust collector outlet, similar increases were observed. (Sections 3.7.5)

- Particle Size

  The largest flyash particles contain the largest combustible fractions. Flyash samples from two spreader stokers and two mass fired overfeed stokers were analyzed. (Sections 3.8.5, 4.7.3)

BOILER EFFICIENCY

- Type of Stoker

  Boiler efficiencies were determined by the ASME Abbreviated Efficiency Test (PTC 4.1). At or near full load, the measured boiler efficiencies ranged from 73.0 to 83.4% for six spreader stokers, 69.8 to 84.1% for seven mass fired overfeed stokers, and 64.1 to 76.8 for five mass fired underfeed stokers. (Sections 3.2, 4.2, 5.6)

- Heat Release Rate

  In most cases, boiler efficiencies were relatively constant with changing heat release rates. At a few sites, efficiency dropped as heat release rate dropped because increasing dry gas heat losses predominated. (Sections 3.3.8, 4.3.8)

- Excess Air

  Boiler efficiency decreased as excess air increased on all of the extensively tested stokers. Dry gas heat losses dominated this trend, overshadowing any effects due to combustible heat losses. For each 10% excess air decrease, boiler efficiency increased by .33% to 1.0%. (Sections 3.4.6, 4.4.6)

- Overfire Air

  Boiler efficiency improved by an average one percent when overfire air was increased on spreader stokers as a result of reduced carbon carryover. However, on mass fired overfeed stokers, efficiency was reduced by an average 2.75% when overfire air was increased due to increased dry gas losses and increased bottom ash combustible heat losses. (Sections 3.6.6, 4.6.6)

- Coal Properties

  Coal properties affected boiler efficiencies on two occasions. At Test Site C, the high moisture western coal produced efficiencies which were 3 to 4% lower than similar tests on low moisture eastern coals. At Test Site K, the unwashed coal produced lower boiler efficiencies than either of the others because this coal led to a greater combustible heat loss. (Sections 3.5.7, 4.5.7)

- Flyash Reinjection

  Some but not all of the carbon in the reinjected flyash was recovered at Sites A, B and C. There was insufficient data to calculate carbon recovery rates with any accuracy. (Section 3.7.5)

1.2 SUMMARY OF FINDINGS ORGANIZED BY TEST VARIABLE

DIFFERENCES BETWEEN STOKER TYPES

- Excess Air

  At full load, most spreader stokers were capable of operating at 30% excess air (5% O_2). By comparison, the mass fired overfeed stokers generally required 50% excess air (7% O_2). (Sections 3.2, 4.2)

  With one exception, the excess air operating level was inversely proportional to the size of the stoker. The larger the stoker, the lower the excess air requirement. (Sections 3.3.1, 4.3.1)

- Particulate Loading

  Spreader stokers with flyash reinjection from their mechanical dust collectors had by far the highest uncontrolled particulate loadings, ranging from 13 to 36 lb/10^6Btu. Spreader stokers without reinjection from their dust collectors were next with emissions of 2.1 to 8.8 lb/10^6Btu, followed by mass fired overfeed stokers with .57 to 2.2 lb/10^6Btu and underfeed stokers with .25 to .71 lb/10^6Btu. (Sections 3.2, 4.2, 5.4)

- Combustibles in the Flyash

  Combustible levels in the flyash were higher in the spreader stokers than in either the mass fired overfeed stokers or the underfeed stokers. With the exception of Test Site C, the spreader stoker data ranged from 47% to 84% and averaged 60%. On the other hand, the mass fired overfeed stoker data ranged from 22% to 56% and averaged 28%. Flyash samples taken from the dust collector hoppers of two underfeed stokers revealed 20.2% and 20.5% combustibles. (Sections 3.2, 4.2, 5.5)

- Combustibles in the Bottom Ash

  Combustible levels were lower in the bottom ash of spreader stokers than they were for mass fired overfeed stokers or underfeed stokers. The average for each of six spreader stokers fired at full load ranged from 0% to 14%. By comparison, mass fired overfeed stokers ranged from 16% to 26% with one unit averaging 43%, and underfeed stokers ranged from 19 to 25% with one unit averaging 8%. (Sections 3.2, 4.2, 5.5)

- Sulfur Oxides

  The spreader stokers retained an average 4.4 percent of the fuel sulfur in the ash, while the mass fired overfeed stokers retained an average 2.1 percent. The remainder was emitted as SO_2 and SO_3, with SO_3 comprising less than two percent of the total. Operating parameters such as excess air, overfire air, and load had no effect on the emissions of sulfur oxides or the retention of sulfur in the ash. (Sections 3.5.3, 4.5.3)

- Nitric Oxide

  As a class, spreader stokers emitted higher concentrations of nitric oxide than did mass fired overfeed stokers. Under full load conditions, spreader stokers emitted between .30 and .61 lb/10^6Btu NOx corrected to NO_2 while mass fired overfeed stokers emitted between .21 and .50 lb/10^6Btu NOx. However, overfeed stokers operated at higher excess air levels than did spreader stokers. When compared at the same excess air levels the difference in NOx levels is even greater. (Sections 3.2, 4.2)

- Carbon Monoxide

  Spreader stokers emitted lower concentrations of carbon monoxide than traveling grate stokers while firing Eastern bituminous coals. Emissions from three of the spreader stokers were in the range of 50 to 250 ppm at full load. A fourth was in the range of 200 to 600 ppm. By comparison, two traveling grate stokers emitted 50 to 700 ppm CO at full load, and a vibrating grate stoker emitted between 50 and 2000+ ppm CO. The comparison is limited to these seven stokers. Carbon monoxide emissions were not measured on three other stokers due to instrument failure, and a fourth fired only Western coals. At Test Sites L1 through L7, the carbon monoxide concentration was measured with an Orsat analyzer having a minimum detection limit of 0.1% or 1000 ppm. Significantly, the carbon monoxide emissions were below this detection limit on the Site L stokers. (Sections 3.2, 4.2)

- Unburned Hydrocarbons

  Based on limited data, the spreader stokers emitted lower hydrocarbon emissions than the mass fired overfeed stokers. Full load emissions from the spreader stoker ranged from 0 to 15 ppm for Site F and 35 to 41 ppm for Site G. By comparison, the mass fired overfeed stokers emitted between 5 and 112 ppm for Site H and 80 ppm for a single point on Site J. (Sections 3.2, 4.2)

- Boiler Efficiency

  Boiler efficiencies were determined by the ASME Abbreviated Efficiency Test (PTC 4.1). At or near full load, the measured boiler efficiencies ranged from 73.0 to 83.4% for six spreader stokers, 69.8 to 84.1% for seven mass fired overfeed stokers, and 64.1 to 76.8 for five mass fired underfeed stokers. (Sections 3.2, 4.2, 5.6)

RESPONSE TO HEAT RELEASE RATE

- Excess Air

  The excess air requirement drops as heat release rate increases on stoker boilers. The excess air requirement levels off as 30% excess air is approached. (Sections 3.3.1, 4.3.1)

- Particulate Loading

  It cannot be said that units with higher design heat release rates have higher particulate loading, but for a given unit the uncontrolled particulate loading always increased as heat release rate, or load, increased. The rate of increase varied from site to site, and at some sites it appeared to accelerate as full load was approached. On spreader stokers with flyash reinjection from mechanical dust collectors, the last 10% increase in heat release rate resulted in a 9 to 20% increase in particulate loading. On spreaders without dust collector reinjection, the increase was 8 to 12%. On mass fired overfeed stokers, particulate loading increased anywhere from 3 to 20% as heat release rate was increased from 90 to 100% of design. (Sections 3.3.2, 4.3.2)

- Combustibles in the Flyash

  Combustibles in the flyash tended to increase slightly as heat release rate increased on spreader stokers. On mass fired overfeed stokers, no significant trend was observed. (Sections 3.3.3, 4.3.3)

- Combustibles in the Bottom Ash

  Heat release rate had very little effect on combustibles in the bottom ash. (Sections 3.3.4, 4.3.4)

- Nitric Oxide

  For spreader stokers, an increase in heat release rate equivalent to 10% of capacity resulted in an average increase in nitric oxide emissions of .025 lb/10^6Btu as NO_2 at constant excess air. For mass fired overfeed stokers, the relationship ranged from zero to .026 lb/10^6Btu per 10% increase in capacity at constant excess air. In all cases, nitric oxide emissions were invarient with load at normal firing conditions because the effects of decreasing excess air effectively canceled the effects of increasing load. Although NOx increased with heat release rate on each given unit, it was not true that units with higher design heat release rates emitted higher concentrations of NOx. (Sections 3.3.5, 4.3.5)

- Carbon Monoxide

  Carbon monoxide emissions were highest at high heat release rates under low excess air conditions, and at low heat release rates under high excess air conditions. At full load, carbon monoxide emissions could be controlled with proper application of combustion air. (Sections 3.3.6, 4.3.6)

- Unburned Hydrocarbons

  Unburned hydrocarbons tended to decrease as heat release rate increased on three of four stokers where this emission was measured. On the fourth stoker, the opposite trend was observed. (Sections 3.3.4, 4.3.7)

- Boiler Efficiency

  In most cases, boiler efficiencies were relatively constant with changing heat release rates. At a few sites, efficiency dropped as heat release rate dropped because increasing dry gas heat losses predominated. (Sections 3.3.8, 4.3.8)

RESPONSE TO EXCESS AIR

- Particulate Loading

  No relationship was established between particulate loading and excess air. This does not foreclose the existence of such a relationship, but rather indicates that such a relationship could not be deciphered from the data due to data scatter and uncontrolled variables. (Sections 3.4.1, 4.4.1)

- Combustibles in the Flyash

  No correlation was found between combustibles in the flyash and excess air level on either spreader stokers or mass fired overfeed stokers. (Sections 3.4.2, 4.4.2)

- Combustibles in the Bottom Ash

  No correlation was found between excess air and combustibles in the bottom ash. (Sections 3.4.2, 4.4.2)

- Nitric Oxide

  On four spreader stokers without air preheat and one with air preheat, nitric oxide increased by .021 to .036 lb/10^6Btu for each increase of 10% excess air. The sixth spreader stoker used air preheat and its NOx increased by .067 lb/10^6Btu per increase of 10% excess air. On five mass fired overfeed stokers, NOx increased by .016 to .027 lb/10^6Btu. (Sections 3.4.3, 4.4.3)

- Carbon Monoxide

  Carbon monoxide was more prevalent as excess air dropped below about 30-40% on spreader stokers and about 60% on mass fired overfeed stokers. Carbon monoxide increased gradually as excess air increased above about 60% on spreader stokers and 100% on mass fired overfeed stokers. (Sections 3.4.4, 4.4.4)

- Unburned Hydrocarbons

  Unburned hydrocarbon emissions showed little or no correlation with excess air on spreader stokers. On mass fired overfeed stokers, hydrocarbons increased in almost direct proportion to the excess air. (Sections 3.4.5, 4.4.5)

- Boiler Efficiency

  Boiler efficiency decreased as excess air increased on all of the extensively tested stokers. Dry gas heat losses dominated this trend, overshadowing any effects due to combustible heat losses. For each 10% excess air decrease, boiler efficiency increased by .33% to 1.0%. (Sections 3.4.6, 4.4.6)

RESPONSE TO COAL COMPOSITION AND SIZING

- Excess Air

  Coal properties were not found to alter excess air requirements on these stoker boilers.

- Particulate Loading

  Because of the movement of air through the grate and the upward movement of combustion gases through the furnace, the smallest coal and ash particles are carried out of the furnace by the gases rather than staying on the grate. This is called particle entrainment and is a problem from both a pollution and an efficiency standpoint. The likelihood of a particle being entrained is a function of its size and density, and the velocities in the furnace. The test data from this program showed a mathematical correlation between coal fines and particulate loading on five stokers. Particulate loading increased by .10 to .55 lb/10^6Btu whenever the percent of coal passing a 16 mesh screen increased by one percent. No correlation was found in studies of six other stokers.

  Coal ash could be related to particulate loading at only four of the ten test sites at which multiple coals were fired. On three of the spreader stokers it was established that particulate loading increased by .24 to .38 lb/10^6Btu for each one percent increase in coal ash. Stated in another way, if the coal ash is doubled at these sites, the particulate loading will increase by 15 to 30%. Thus, the relationship between coal ash and particulate loading was not one-to-one on these three units.

  On one of the traveling grate stokers, a 4% ash washed coal and a 10% ash unwashed coal from the same mine were tested. The 250% increase in coal ash resulted in a 300% increase in particulate loading. In this case, the dramatic increase in particulate loading can be attributed to the type of ash, a clay like material in the surface of the coal, and to a corresponding increase in coal fines on the unwashed coal. (Sections 3.5.1, 4.5.1)

- Combustibles in the Flyash

  At Test Site C, the combustibles in the flyash were 2 to 4 times higher while firing an Eastern bituminous coal than while firing a Western sub-bituminous coal. This was the only site where flyash combustibles could be directly related to coal properties. The particular property of the coal responsible for the difference was not identified. (Sections 3.5.2, 4.5.2)

- Combustibles in the Bottom Ash

  It was found that 65% to 85% of the coal ash remained on the grate in spreader stokers as compared to 80% to 90% for mass fired overfeed stokers. For the purposes of computing combustible heat losses, 75% and 85% are good estimates for spreaders and mass fired overfeed stokers, respectively.

  Small differences in bottom ash combustible levels were observed which appeared to be related to coal properties at some sites. However, the particular coal properties causing these differences were not identified. (Sections 3.5.2, 4.5.2)

- Sulfur Oxides

  Although good sulfur balances were difficult to obtain, the data indicates that fuel sulfur conversion efficiencies of 95 to 98% are reasonable assumptions. (Sections 3.5.3, 4.5.3)

- Nitric Oxide

  Variations in fuel nitrogen from .75% to 1.50% by weight had no measurable effect on nitric oxide emissions. This may simply reflect difficulties in sorting out the other variables. (Section 3.5.4, 4.5.4)

- Carbon Monoxide

  Carbon monoxide emissions were greatest while firing Western subbituminous coals. On one spreader stoker where both an Eastern and a Western coal were fired, the full load Western coal emissions ranged from 163 to 702 ppm and averaged 342 ppm. By comparison, the full load Eastern coal emissions ranged from 33 to 263 ppm and averaged 71 ppm. (Sections 3.5.5, 4.5.5)

- Unburned Hydrocarbons

  The site firing the lower volatile coal had the lowest hydrocarbon emissions. The 29% volatile coal yielded 19-41 ppm hydrocarbons while the 41% volatile coal yielded 163 to 602 ppm hydrocarbons. Volatiles are expresssed here on a dry, mineral matter free basis. (Sections 3.5.6, 4.5.6)

- Boiler Efficiency

  Coal properties affected boiler efficiencies on two occasions. At Test Site C, the high moisture western coal produced efficiencies which were 3 to 4% lower than similar tests on low moisture eastern coals. At Test Site K, the unwashed coal produced lower boiler efficiencies than either of the others because this coal led to a greater combustible heat loss. (Sections 3.5.7, 4.5.7)

RESPONSE TO OVERFIRE AIR

- Particulate Loading

  Uncontrolled particulate loading was reduced by 20 to 50% on four of six spreader stokers and three of five mass fired overfeed stokers when overfire air pressures were increased. Two sites showed the opposite trend and two sites were unaffected by changes in overfire air pressure. (Sections 3.6.1, 4.6.1)

- Combustibles in the Flyash

  Increasing overfire air pressure effectively reduced the combustible content of the flyash by an average 40% in 74% of the overfire air tests. This resulted in an average efficiency gain of 1.70% of heat input for spreader stokers and 0.27% of heat input for the mass fired overfeed stokers. 26% of the tests gave the opposite result. (Sections 3.6.2, 4.6.2)

- Nitric Oxide

  Nitric oxide emissions were not influenced by changes in overfire air pressure when considered at constant excess air. (Sections 3.6.3, 4.6.3)

- Carbon Monoxide

  Carbon monoxide emissions were reduced by the increased use of overfire air. (Sections 3.6.4, 4.6.4)

- Unburned Hydrocarbons

  Unburned hydrocarbons were reduced 82% by increasing the overfire air pressure on one traveling grate stoker. No correlation was found on one spreader stoker. The other two units where hydrocarbon emissions were measured had insufficient data to make a correlation. (Sections 3.6.5, 4.6.5)

- Boiler Efficiency

  Boiler efficiency improved by an average one percent when overfire air was increased on spreader stokers as a result of reduced carbon carryover. However, on mass fired overfeed stokers, efficiency was reduced by an average 2.75% when overfire air was increased due to increased dry gas losses and increased bottom ash combustible heat losses. (Sections 3.6.6, 4.6.6)

RESPONSE TO FLYASH REINJECTION

- Particulate Loading

  Flyash from the dust collector was reinjected to the furnace of three of the six spreader stokers. In each case it was demonstrated that uncontrolled particulate loading was increased as a result of reentrainment of a portion of the reinjected ash. At one site, reinjection was completely eliminated for test purposes. As a result, uncontrolled particulate loading was reduced by 70 to 80% and controlled particulate loading was reduced by 40 to 50%. Reducing the degree of flyash reinjection reduced the percentage of larger particles in the flyash. This in turn reduced the mechanical dust collector efficiency. (Sections 3.7.4, 3.7.6)

- Combustibles in the Flyash

  Combustibles in the flyash at the boiler outlet increased by 23% to 63% when the rate of flyash reinjection was reduced. At the dust collector outlet, similar increases were observed. (Sections 3.7.5)

- Nitric Oxide

  Flyash reinjection from the mechanical dust collector had no measurable effect on nitric oxide emissions. (Section 3.7)

- Carbon Monoxide

  Flyash reinjection from the mechanical dust collector had no measurable effect upon carbon monoxide emissions. (Section 3.7)

- Boiler Efficiency

  Some but not all of the carbon in the reinjected flyash was recovered at Sites A, B and C. There was insufficient data to calculate carbon recovery rates with any accuracy. (Section 3.7.5)

PARTICLE SIZE DISTRIBUTION

- Particulate Loading

  Particle size distribution of the flyash was determined by a variety of methods including cascade impactor, Bahco classifier, SASS cyclones and sieve analysis. The results varied from one method of measurement to another, but clearly showed that spreader stokers emit a higher percentage of coarse, more easily collected particles than mass fired overfeed and underfeed stokers. (Sections 3.8, 4.7, 5.7)

- Combustibles in the Flyash

  The largest flyash particles contain the largest combustible fractions. Flyash samples from two spreader stokers and two mass fired overfeed stokers were analyzed. (Sections 3.8.5, 4.7.3)

EMISSION FACTORS

- Particulate Loading

  U.S. Environmental Protection Agency Publication AP-42, Compilation of Air Pollutant Emission Factors, Third Edition, contains factors used for predicting emissions from stoker-boilers. The data from this program compares as follows: (Sections 3.2, 4.2, 5.4)

	Uncontrolled Particulates, lb/ton (A = % Ash in Coal)	
	AP-42	This Program
Spreaders with Reinjection	20A	29A - 50A
Spreaders without Reinjection	13A	14A - 17A
Overfeed Stokers	5A	1.1A - 3.8A
Underfeed Stokers	5A	.6A - 1.7A

- Nitric Oxides

  U.S. Environmental Protection Agency publication AP-42, Compilation of Air Pollutant Emission Factors, Third Edition, contains factors used for predicting emissions from stoker boilers. The data from this program compares as follows: (Sections 3.2, 4.2)

	Nitrogen Oxides, lb/ton	
	AP-42	This Program
Spreader Stokers	15	9.4 - 14.2
Overfeed Stokers	None	7.1 - 9.4

2.0 INTRODUCTION

In late 1977, the American Boiler Manufacturers Association (ABMA) was awarded a contract to update specifications and design parameters for coal burning boiler and stoker equipment. The project was jointly funded by the United States Department of Energy and the United States Environmental Protection Agency, with the express purpose of increasing coal usage in an environmentally acceptable manner.

2.1 THE NEED

The need for such a program is clear. In recent years the vast majority of industrial boiler installations have been packaged or shop assembled gas and oil fired units. These boilers could be purchased and installed at substantially lower costs than conventional coal burning boiler-stoker equipment. Because of the declining demand for coal stokers, little or no work has been done in recent years to improve specification data or product information made available to consulting engineers and purchasers of coal burning boiler-stoker equipment.

Furthermore, the market for coal suitable to be fired in industrial boilers is being held back by critical uncertainties in the environmental and energy areas, causing potential customers of coal-fired industrial boilers to shelve plans for capital expansion and conversion. The current implementation of more rigid air pollution regulations has made it difficult for many coal burning installations to comply with required stack emission limits.

It is highly desirable to remove these uncertainties and thereby encourage industrial users to order and install coal stoker fired boilers. This would lead to significantly increased coal usage and decreased dependence upon scarce and imported fuels.

2.2 THE OBJECTIVES

The objectives of this program are:

1. To advance stoker boiler technology through comprehensive testing of various stoker boiler designs, thereby facilitating the design and fabrication of stoker boilers which are economically and environmentally satisfactory alternatives to gas and oil fired units.

2. To contribute to the design and application of pollution control equipment by generating a large data base of boiler outlet dust loading data and particle size distribution data.

3. To provide guidelines for boiler operator's concerning techniques for clean and efficient stoker boiler operation.

4. To facilitate preparation of intelligent and reasonable national emission standards for coal fired stoker boilers by the United States Environmental Protection Agency.

5. To provide assistance in planning for coal supply contracts both through an increased knowledge of the effects of coal properties on emissions, and through the development of reasonable emission regulations.

6. To promote the increased utilization of coal fired stoker boilers by the United States industry by insuring compatibility of these units emissions with the applicable environmental requirements.

2.3 THE PROJECT ORGANIZATION

The American Boiler Manufacturers Association formed a Stoker Technical Committee composed of personnel from member companies to oversee the project. The committee, in turn, subcontracted the field testing and report work to KVB, Inc., a combustion consulting firm located in Minneapolis, Minnesota. The original scope of work included the testing of six spreader stokers. Testing on the first unit began August 9, 1977.

As the project progressed successfully, additional funding was obtained and the scope of work was increased to include five mass fired overfeed stokers. These units were also tested by KVB, Inc.

A separate subcontract was let to Pennsylvania State University to test seven small stoker boilers including two overfeed stokers and five underfeed stokers located in central steam heating plants.

On November 12, 1979, all testing was completed. A total of 400 tests on 18 stoker boilers and 36 boiler-coal combinations had been conducted.

2.4 THE TEST REPORTS

This report is the final technical report for the stoker test program. Many reports have preceded it and several are to follow.

A technical report and a data supplement were prepared for each of the eleven extensively tested boilers.[1-22] These "Site Reports" are identified by the letter designators A through K to protect the interests of the host facilities. No mention is made of site location. The seven boilers tested under separate subcontract were less extensively tested than Sites A through K. These seven boilers were tested for particulate loading and particle size distribution at a single operating condition. For this reason, these seven sites are identified as L1 through L7 and their test results are reported under one cover called the "Site L1-L7 Report."[23, 24] Each site report is approximately 100 pages in length and may be obtained through the EPA's Center for Environmental Research Information (CERI) or through NTIS. Ordering information is included in the Appendix to this report.

The data supplements accompanying the site reports are only of value to those who wish to study the data in greater detail than is presented in the Site report. Each data supplement is a compilation of hand written data sheets, and is not a required companion to the site report.

The following report consolidates the test results of all eighteen stoker boilers. It is divided into three major sections according to stoker classification: spreader stokers, mass fired overfeed stokers, and underfeed stokers. Within each section the stoker boilers are described and the test results summarized. Extensive use is made of figures and tables to present the data.

Because the data base is so large, all of the data from each site cannot be included in this final report. Instead, a Data Supplement to the final report has been prepared which contains several hundred data plots and data tables. The data supplement is not referenced in this report. However, the data supplement is available to those who wish to study the data in greater detail.

This final report does not mention the names of the equipment manufacturers. The ABMA Stoker Technical Committee felt that such information could lead to false association of unit performance with a specific manufacturer when, in fact, unit performance can relate to any number of variables including fuel properties and operating procedures. Any superficial association between unit performance and manufacturer would be a grievous mistake.

Two additional reports are being prepared under this contract. One report will be addressed to stoker boiler operators, identifying operating procedures which lead to increased combustion efficiency and reduced emissions. The other report will summarize the results of EPA Level 1 chemical analysis on test sites A through K for polynuclear aromatic hydrocarbons and trace elements.

3.0 SPREADER STOKERS

3.1 DESCRIPTION OF UNITS TESTED

A spreader stoker is an overfeed stoker that discharges the fuel into the furnace from mechanical feeders located above the grate. These feeders throw the fuel onto a grate which travels toward the feeder. Spreader stokers are characterized by a thin fuel bed on the grate and partial suspension burning. They are studied as a separate group in this report because their burning characteristics are uniquely different from other types of stokers.

The six spreader stokers tested for this program represent a wide range of state-of-the-art designs. They were all built between 1973 and 1976. They span the range of capacities most commonly specified for this type of unit, ranging in capacity from 75,000 lb steam/hr to 300,000 lb steam/hr. Three of the stokers are equipped with flyash reinjection from their mechanical dust collector. Two are of the multiple pass or baffled boiler design, and all are equipped with traveling grates and continuous front ash discharge. Table 3-1 gives a brief description of each unit tested.

TABLE 3-1

DESCRIPTION OF SPREADER STOKERS TESTED

Site	Year Built	Steaming Capacity lb/hr	Flyash Reinjection From DC	Boiler Passes	Backend Equipment by Order of Occurrence
A	1976	300,000	Yes	Single	AH, DC, ESP, ECON, SCR
B	1974	200,000	Yes	Single	DC, ECON, ESP
C	1975	182,500	Yes	Single	DC, ECON, AH, ESP
E	1973	180,000	No	Single	ECON, DC
F	1976	80,000	No	Multiple	ECON, DC
G	1974	75,000	No	Multiple	DC

The following pages present equipment data and a general arrangement drawing of each spreader stoker tested. Throughout this report the units will be referred to by the letter designation assigned in this section.

TABLE 3-2

EQUIPMENT DATA
TEST SITE: A

BOILER:

Year Built	1976
Configuration	Single Pass
Rated Steaming Capacity	300,000 lb/hr
Design Pressure	350 psig
Actual Operating Pressure	320 psig
Feedwater Temperature	240°F
Steam Temperature	Saturated
Operating Air Temperature	315°F

STOKER:

Classification	Spreader with Traveling Grate
Effective Length	19.0 Ft
Width	27.1 Ft
Effective Grate Area	515.4 Ft^2

HEATING SURFACES:

Furnace Volume	16,712 Ft^3
Water Wall	2,982 Ft^2
Boiler	20,186 Ft^2
Superheater	None
Economizer	13,276 Ft^2
Air Heater	Unknown

HEAT RATES AT RATED CAPACITY:

Input to Furnace	359,000,000 Btu/hr
Grate Width Heat Release	13,200,000 Btu/hr-ft
Grate Heat Release	696,000 Btu/hr-ft^2
Furnace Liberation	21,500 Btu/hr-ft^3

OVERFIRE AIR:

Location	Front Upper	Front Lower	Rear Upper	Rear Lower
Number of Jets x Pipe Size	25x*	30x3/4"	25x*	27x1"
Elevation Above Grate	6.5 Ft	1.5 Ft	6.0 Ft	2.2 Ft
Inclination below Horizontal	19°	0°	9°	0°

FLYASH REINJECTION:

Flyash Source	Boiler Hopper	AH Hopper	DC Hopper
Number of Injectors	6	7	12
Elevation above Grate	1.3 Ft	1.3 Ft	1.3 Ft
Inclination below Horizontal	4.5°	4.5°	4.5°

EMISSION CONTROL EQUIPMENT:	Mechanical Collector Electrostatic Precipitator Wet Scrubber

* Front upper and rear upper overfire air jets have openings of 7/8"x1-5/16"

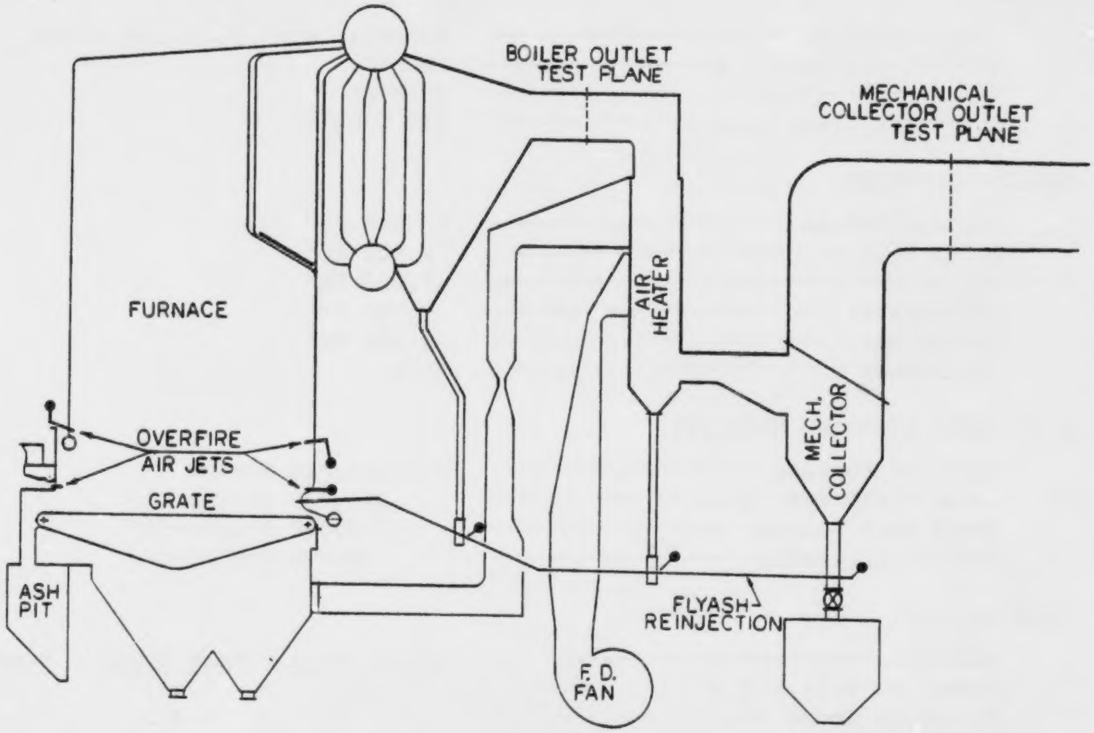
BOILER OUTLET TEST PLANE
MECHANICAL COLLECTOR OUTLET TEST PLANE
FURNACE
AIR HEATER
MECH. COLLECTOR
OVERFIRE AIR JETS
GRATE
ASH PIT
FLYASH REINJECTION
F. D. FAN

Figure 3-1. Test Site A General Arrangement Drawing

TABLE 3-3

EQUIPMENT DATA
TEST SITE: B

BOILER:

Year Built	1974
Configuration	Single Pass
Rated Steaming Capacity	200,000 lb/hr
Design Pressure	750 psig
Actual Operating Pressure	185 psig
Feedwater Temperature	225°F
Steam Temperature	500°F
Operating Air Temperature	Ambient

STOKER:

Classification	Spreader with Traveling Grate
Effective Length	18.5 Ft
Width	20.0 Ft
Effective Grate Area	370.0 Ft^2

HEATING SURFACES:

Furnace Volume	12,910 Ft^3
Water Wall	2,820 Ft^2
Boiler	15,038 Ft^2
Superheater	1,900 Ft^2
Economizer	4,110 Ft^2
Air Heater	None

HEAT RATES AT RATED CAPACITY:

Input to Furnace	264,000,000 Btu/hr
Grate Width Heat Release	13,200,000 Btu/hr-ft
Grate Heat Release	713,000 Btu/hr-ft^2
Furnace Liberation	20,400 Btu/hr-ft^3

OVERFIRE AIR:

Location	Front Upper	Rear Upper	Rear Lower
Number of Jets x Pipe Size	17x1½"	17x1½"	17x1½"
Elevation Above Grate	7.8 Ft	5.8 Ft	2.0 Ft
Inclination below Horizontal	18°	2.5°	2.5°

FLYASH REINJECTION:

Flyash Source	Boiler Hopper	DC Hopper
Number of Injectors	6	7
Elevation above Grate	1.5 Ft	1.5 Ft
Inclination below Horizontal	7°	7°

EMISSION CONTROL EQUIPMENT:	Selective Type Mechanical Collector Electrostatic Precipitator

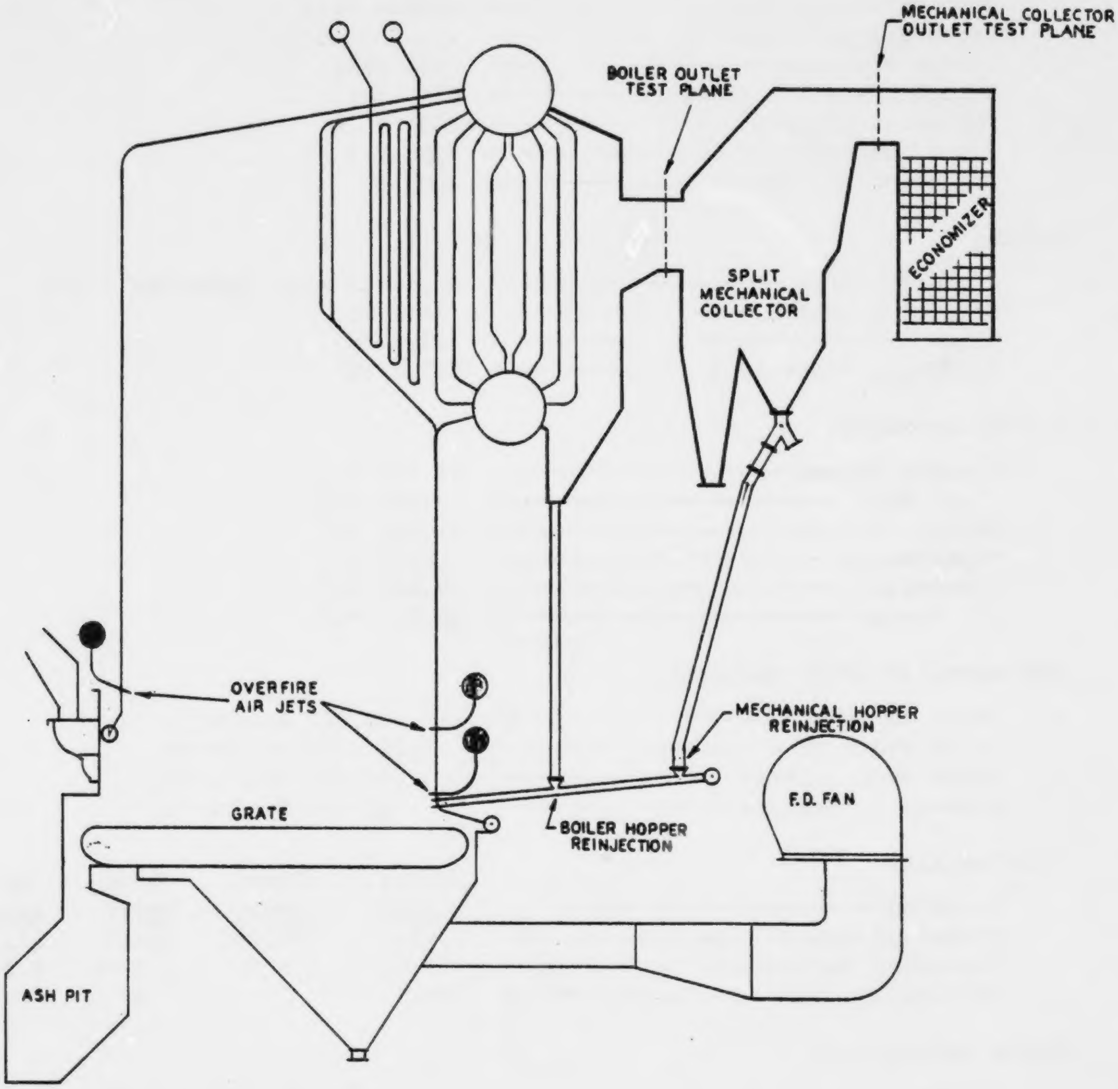
MECHANICAL COLLECTOR OUTLET TEST PLANE
BOILER OUTLET TEST PLANE
SPLIT MECHANICAL COLLECTOR
ECONOMIZER
OVERFIRE AIR JETS
MECHANICAL HOPPER REINJECTION
GRATE
BOILER HOPPER REINJECTION
F.D. FAN
ASH PIT

Figure 3-2. Test Site B General Arrangement Drawing

KVB 4-15900-554

TABLE 3-4

EQUIPMENT DATA
TEST SITE: C

BOILER:

Year Built	1975
Configuration	Single Pass
Rated Steaming Capacity	182,500 lb/hr
Design Pressure	1025 psig
Actual Operating Pressure	875 psig
Feedwater Temperature	370° F
Steam Temperature	900° F
Operating Air Temperature	300° F

STOKER:

Classification	Spreader with Traveling Grate
Effective Length	19.0 Ft
Width	27.1 Ft
Effective Grate Area	515.4 Ft^2

HEATING SURFACES:

Furnace Volume	12,100 Ft^3
Water Wall	2,906 Ft^2
Boiler	21,925 Ft^2
Superheater	10,520 Ft^2
Economizer	8,620 Ft^2
Air Heater	22,217 Ft^2

HEAT RATES AT RATED CAPACITY:

Input to Furnace	249,000,000 Btu/hr
Grate Width Heat Release	9,190,000 Btu/hr-ft
Grate Heat Release	483,000 Btu/hr-ft^2
Furnace Liberation	20,600 Btu/hr-ft^3

OVERFIRE AIR:

Location	Front Upper	Front Lower	Rear Upper	Rear Lower
Number of Jets x Pipe Size	27x3/4"	29x3/4"	28x1"	13x1¼"
Elevation Above Grate	6.3 Ft	1.5 Ft	6.1 Ft	1.5 Ft
Inclination below Horizontal	25°	0°	9°	0°

FLYASH REINJECTION:

Flyash Source	Boiler Hopper	DC Hopper
Number of Injectors	7	16
Elevation above Grate	1.5 Ft	1.5 Ft
Inclination below Horizontal	4°	4°

EMISSION CONTROL EQUIPMENT:	Selective Type Mechanical Collector Electrostatic Precipitator

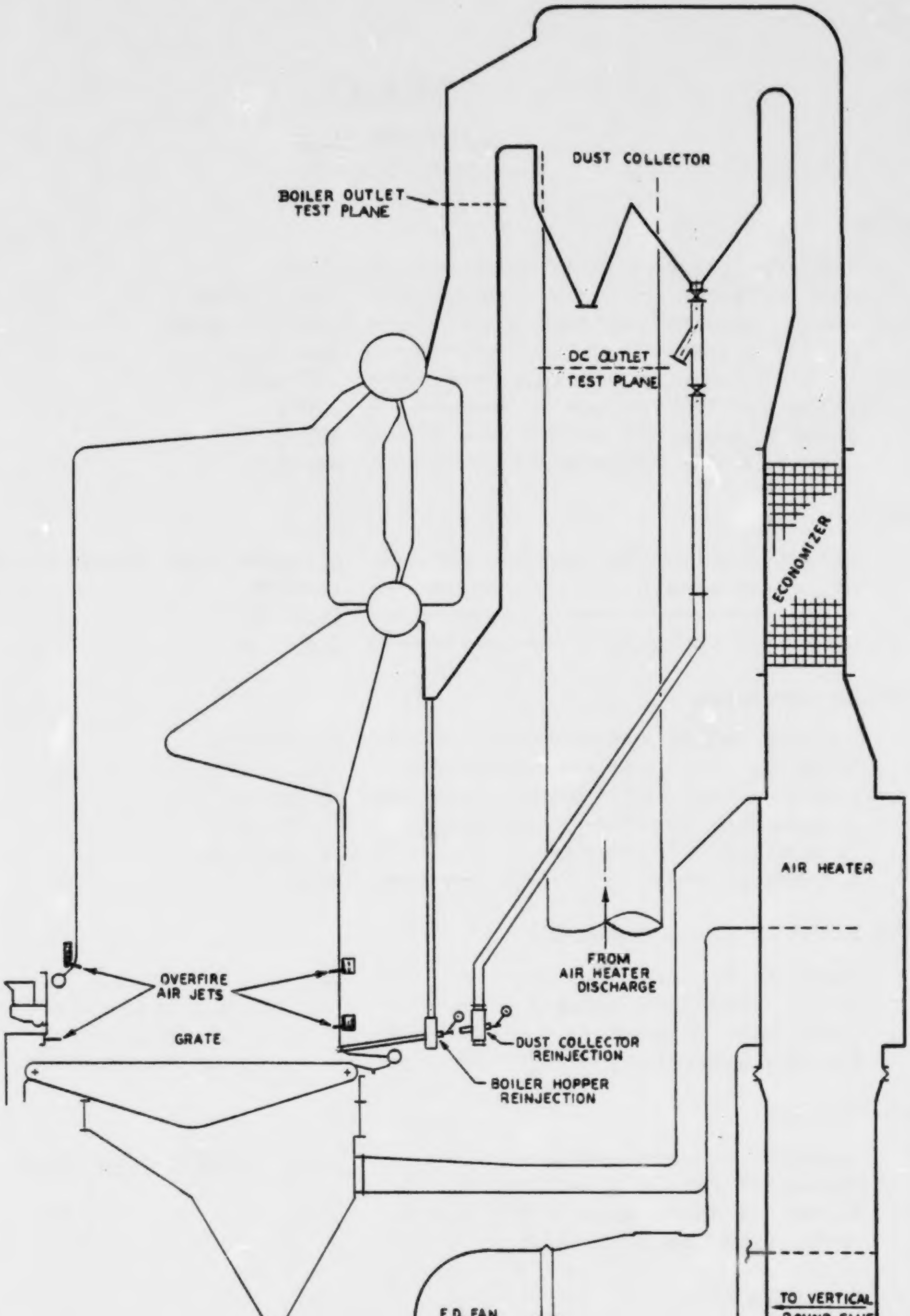
DUST COLLECTOR
BOILER OUTLET TEST PLANE
DC OUTLET TEST PLANE
ECONOMIZER
AIR HEATER
FROM AIR HEATER DISCHARGE
OVERFIRE AIR JETS
GRATE
DUST COLLECTOR REINJECTION
BOILER HOPPER REINJECTION
F.D. FAN
TO VERTICAL ROUND FLUE

Figure 3-3. Test Site C General Arrangement Drawing

TABLE 3-5

EQUIPMENT DATA
TEST SITE: E

BOILER:

Year Built	1973
Configuration	Single Pass
Rated Steaming Capacity	180,000 lb/hr
Design Pressure	250 psig
Actual Operating Pressure	175 psig
Feedwater Temperature	220°F
Steam Temperature	427°F
Operating Air Temperature	Ambient

STOKER:

Classification	Spreader with Traveling Grate
Effective Length	21.5 Ft
Width	16.0 Ft
Effective Grate Area	344.0 Ft^2

HEATING SURFACES:

Furnace Volume	10,255 Ft^3
Water Wall	2,850 Ft^2
Boiler	13,402 Ft^2
Superheater	480 Ft^2
Economizer	6,350 Ft^2
Air Heater	None

HEAT RATES AT RATED CAPACITY:

Input to Furnace	232,000,000 Btu/hr
Grate Width Heat Release	14,500,000 Btu/hr-ft
Grate Heat Release	674,000 Btu/hr-ft^2
Furnace Liberation	22,600 Btu/hr-ft^3

OVERFIRE AIR:

Location	Front Upper	Rear Upper	Rear Lower
Number of Jets x Pipe Size	8	8	8
Elevation Above Grate	6.5 Ft	6.0 Ft	2.0 Ft
Inclination below Horizontal	15°	0°	0°

FLYASH REINJECTION:

Flyash Source	Boiler Hopper
Number of Injectors	Unknown
Elevation above Grate	1.3 Ft
Inclination below Horizontal	5°

EMISSION CONTROL EQUIPMENT:	Mechanical Collector

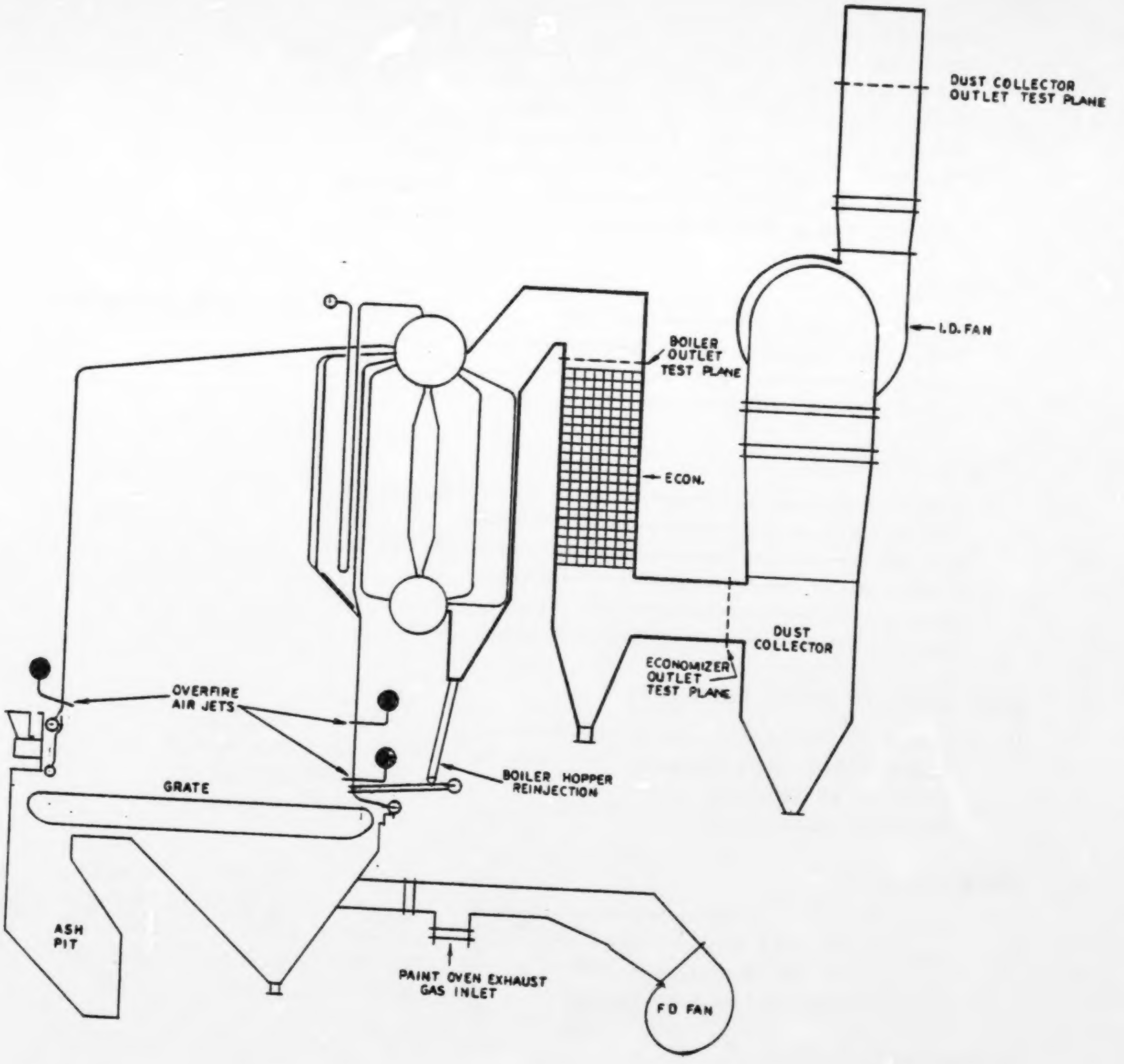
DUST COLLECTOR OUTLET TEST PLANE
I.D. FAN
BOILER OUTLET TEST PLANE
ECON.
DUST COLLECTOR
ECONOMIZER OUTLET TEST PLANE
OVERFIRE AIR JETS
BOILER HOPPER REINJECTION
GRATE
ASH PIT
PAINT OVEN EXHAUST GAS INLET
F D FAN

Figure 3-4. Test Site E General Arrangement Drawing

TABLE 3-6

EQUIPMENT DATA
TEST SITE: F

BOILER:

Year Built	1976
Configuration	Multiple Pass
Rated Steaming Capacity	80,000 lb/hr
Design Pressure	200 psig
Actual Operating Pressure	150 psig
Feedwater Temperature	228°F
Steam Temperature	Saturated
Operating Air Temperature	Ambient

STOKER:

Classification	Spreader with Traveling Grate
Effective Length	13.0 Ft
Width	10.9 Ft
Effective Grate Area	141.4 Ft^2

HEATING SURFACES:

Furnace Volume	4,105 Ft^3
Water Wall	777 Ft^2
Boiler	8,203 Ft^2
Superheater	None
Economizer	3,017 Ft^2
Air Heater	None

HEAT RATES AT RATED CAPACITY:

Input to Furnace	97,300,000 Btu/hr
Grate Width Heat Release	8,950,000 Btu/hr-ft
Grate Heat Release	688,000 Btu/hr-ft^2
Furnace Liberation	23,500 Btu/hr-ft^3

OVERFIRE AIR:

Location	Front Upper	Front Lower	Rear Upper	Rear Lower
Number of Jets x Pipe Size	9x3/4"	11x3/4"	14x3/4"	7x1"
Elevation Above Grate	6.0 Ft	1.5 Ft	6.0 Ft	1.0 Ft
Inclination below Horizontal	26°	0°	11°	0°

FLYASH REINJECTION:

Flyash Source	Boiler Hopper	Econ. Hopper
Number of Injectors	4	3
Elevation above Grate	1.3 Ft	1.3 Ft
Inclination below Horizontal	6.5°	6.5°

EMISSION CONTROL EQUIPMENT: Mechanical Collector

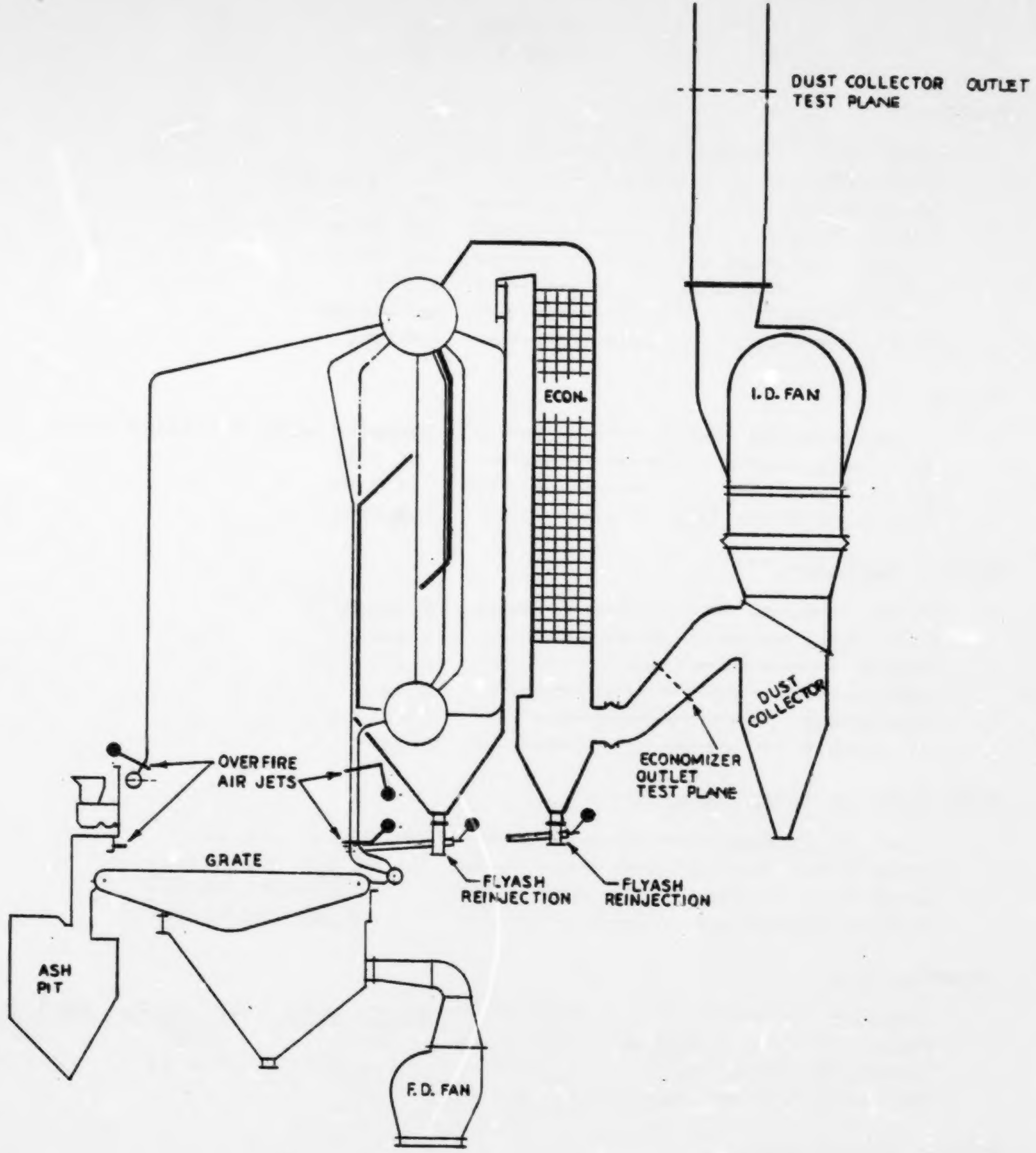
DUST COLLECTOR OUTLET
TEST PLANE
ECON.
I.D. FAN
DUST COLLECTOR
ECONOMIZER
OUTLET
TEST PLANE
OVER FIRE
AIR JETS
GRATE
FLYASH
REINJECTION
FLYASH
REINJECTION
ASH
PIT
F.D. FAN

Figure 3-5. Test Site F General Arrangement Drawing

TABLE 3-7

EQUIPMENT DATA
TEST SITE: G

BOILER:

Year Built	1974
Configuration	Multiple Pass
Rated Steaming Capacity	75,000 lb/hr
Design Pressure	200 psig
Actual Operating Pressure	160 psig
Feedwater Temperature	212°F
Steam Temperature	Saturated
Operating Air Temperature	Ambient

STOKER:

Classification	Spreader with Traveling Grate
Effective Length	14.2 Ft
Width	9.8 Ft
Effective Grate Area	139.0 Ft^2

HEATING SURFACES:

Furnace Volume	4,120 Ft^3
Water Wall	2,140 Ft^2
Boiler	8,280 Ft^2
Superheater	None
Economizer	None
Air Heater	None

HEAT RATES AT RATED CAPACITY:

Input to Furnace	99,000,000 Btu/hr
Grate Width Heat Release	10,100,000 Btu/hr-ft
Grate Heat Release	712,000 Btu/hr-ft^2
Furnace Liberation	24,000 Btu/hr-ft^3

OVERFIRE AIR:

Location	Front Lower	Rear Upper	Rear Lower
Number of Jets x Pipe Size	12x1"	14x1"	11x1"
Elevation Above Grate	1.4 Ft	5.6 Ft	1.8 Ft
Inclination below Horizontal	0°	5°	5°

FLYASH REINJECTION:

Flyash Source	Boiler Hopper
Number of Injectors	3
Elevation above Grate	1.8 Ft
Inclination below Horizontal	5°

EMISSION CONTROL EQUIPMENT:	Mechanical Collector

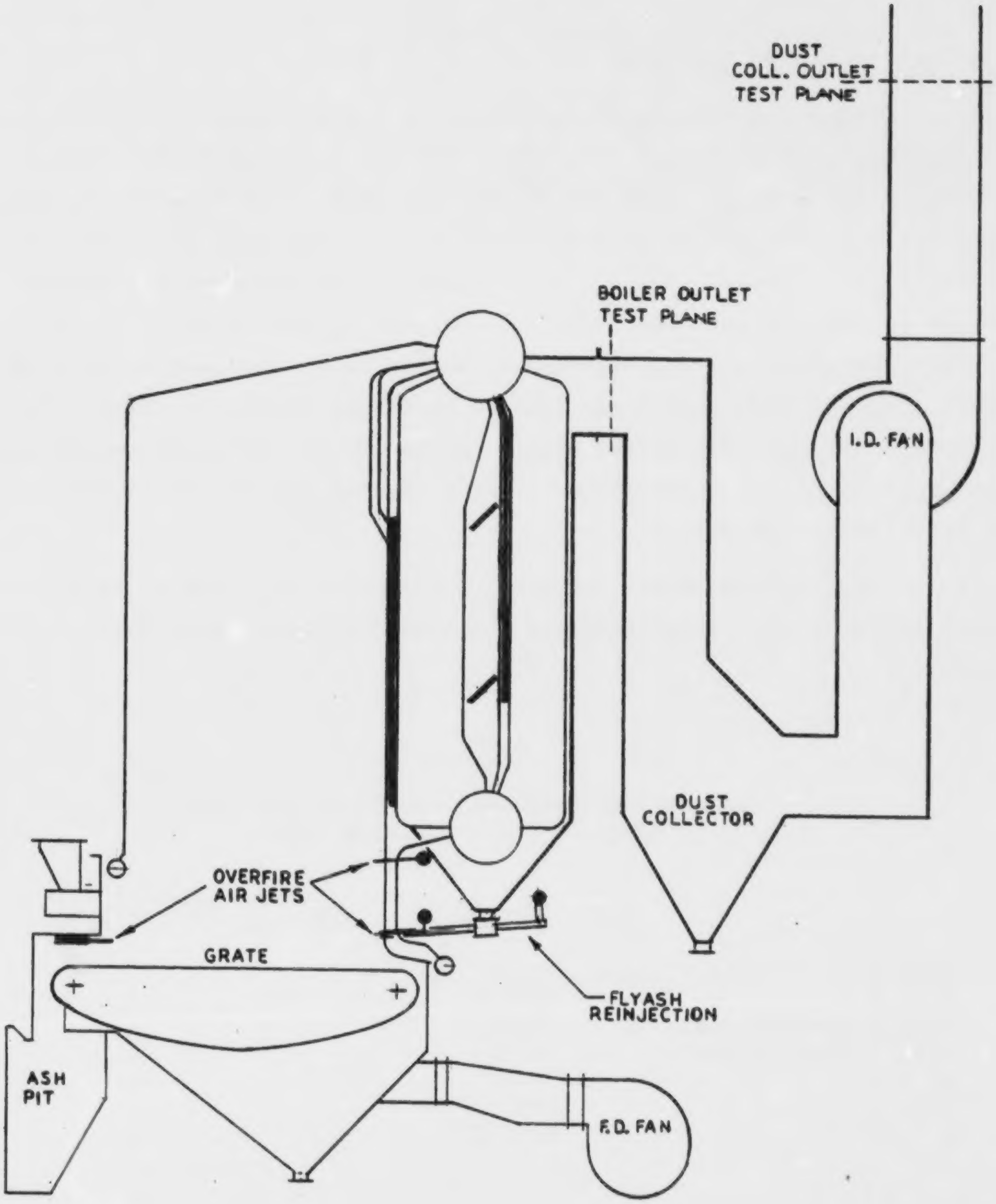
DUST
COLL. OUTLET
TEST PLANE
BOILER OUTLET
TEST PLANE
I.D. FAN
DUST
COLLECTOR
OVERFIRE
AIR JETS
GRATE
FLYASH
REINJECTION
ASH
PIT
F.D. FAN

Figure 3-6. Test Site G General Arrangement Drawing

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3.2 PERFORMANCE AT FULL LOAD

This section presents the emissions and efficiency data for six spreader stokers operated at or near full load. For the purposes of this report, full load is defined as the upper 10% of the load range obtainable at the time of testing. For four of the spreader stokers this represents 90 to 100% of nameplate rating. However, Sites A and E could not be operated at nameplate rating at the time of these tests. The stoker at Site A was in its first months of operation after initial startup and had an unresolved problem with its forced draft system. Thus, Site A was limited to 87% of nameplate rating. The stoker at Site E had been retrofitted with a new combustion air system which limited its capacity to 73% of nameplate. The new system was limited by the capacity of its forced draft fan.

The capacity ranges selected to represent full load at each site are shown in Table 3-8. Also shown are the number of tests which make up the data base.

TABLE 3-8

CAPACITY RANGE AND DATA BASE FOR FULL LOAD TESTS ON SIX SPREADER STOKERS

		Number of Tests	
	% Capacity Range	Gaseous	Particulate
Site A	80-87	9	6
Site B	96-100	9	4
Site C (Eastern Coal)	91-99	26	9
Site C (Western Coal)	95-102	19	8
Site E	65-73	10	6
Site F	97-102	22	7
Site G	97-102	13	4
	TOTALS	108	44

The Site C performance data are presented in two parts because of the significant differences observed when burning an Eastern and a Western coal.

The figures in this section indicate minimums, maximums and averages of the measured data for each parameter and test site as measured within the load ranges specified in Table 3-8. Each figure is accompanied by a brief discussion of the data.

The data are representative of as-found operating practice. The range of data shown represents normal variations which might be experienced in day-to-day operation.

Extremes should be treated with caution when interpreting these data. There is a certain degree of scatter, or uncertainty, to the data which must be taken into account. Thus, for example, if a certain unit emitted a very low particulate loading during one test, it does not follow that this unit can operate continuously at the low particulate loading by simply duplicating the stoker settings of the test.

3.2.1 Emission Factors

U.S. Environmental Protection Agency publication AP-42, Compilation of Air Pollutant Emission Factors, Third Edition, contains factors used for predicting emissions from spreader stokers. The full load data from this test program have been converted to the same units used in AP-42 to obtain a set of measured emission factors. These are presented in Tables 3-9 and 3-10. The bituminous and sub-bituminous coal data are presented separately since AP-42 addresses only bituminous coal firing. It is observed that the AP-42 emission factor for uncontrolled particulate loading from spreader stokers is lower than the measured values, while the AP-42 emission factor for Nitrogen Oxides is higher than the measured values.

TABLE 3-9

EMISSION FACTORS FOR SPREADER STOKERS FIRING BITUMINOUS COAL

	Uncontrolled Particulates, lb/ton		
	With Reinjection	Without Reinjection	Nitrogen Oxides lb/ton
Site B	29 A*	--	9.4
Site C	50 A	14.6 A	11.5
Site E	--	13.7 A	14.2
Site F	--	15.8 A	11.4
Site G	--	16.8 A	12.5
Average	40 A	15 A	12
AP-42	20 A	13 A	15

TABLE 3-10

EMISSION FACTORS FOR SPREADER STOKERS FIRING SUB-BITUMINOUS COAL

	Uncontrolled Particulates, lb/ton		
	With Reinjection	Without Reinjection	Nitrogen Oxides lb/ton
Site A	60 A	--	11.4
Site C	58 A	14.5 A	8.6

*The letter A indicates that the weight percentage of ash in the coal should be multiplied by the given value.

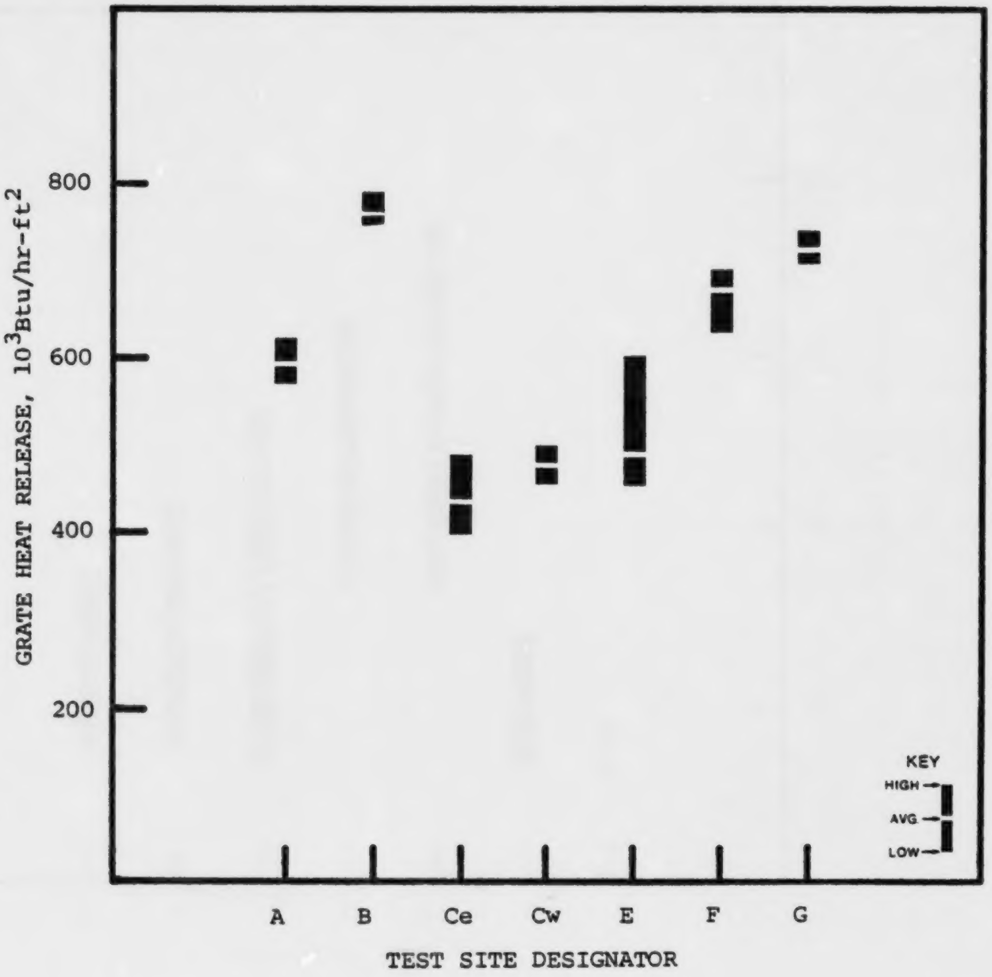

Figure 3-7. Grate Heat Release Rates of Six Spreader Stokers Fired at Full Load.

The ranges of grate heat release rates shown here correspond to full load operation as defined in Table 3-8. The ABMA guideline for stoker applications firing bituminous coal specifies a maximum grate heat release rate of no more than 750,000 Btu per hour per square foot of effective air admitting grate area. All six spreader stokers were designed and operated below this suggested maximum. Sites A and E show relatively low grate heat release rates because they were not operated at their nameplate ratings. Site C is low by design. This unit was designed for future upgrading to a higher pressure and capacity.

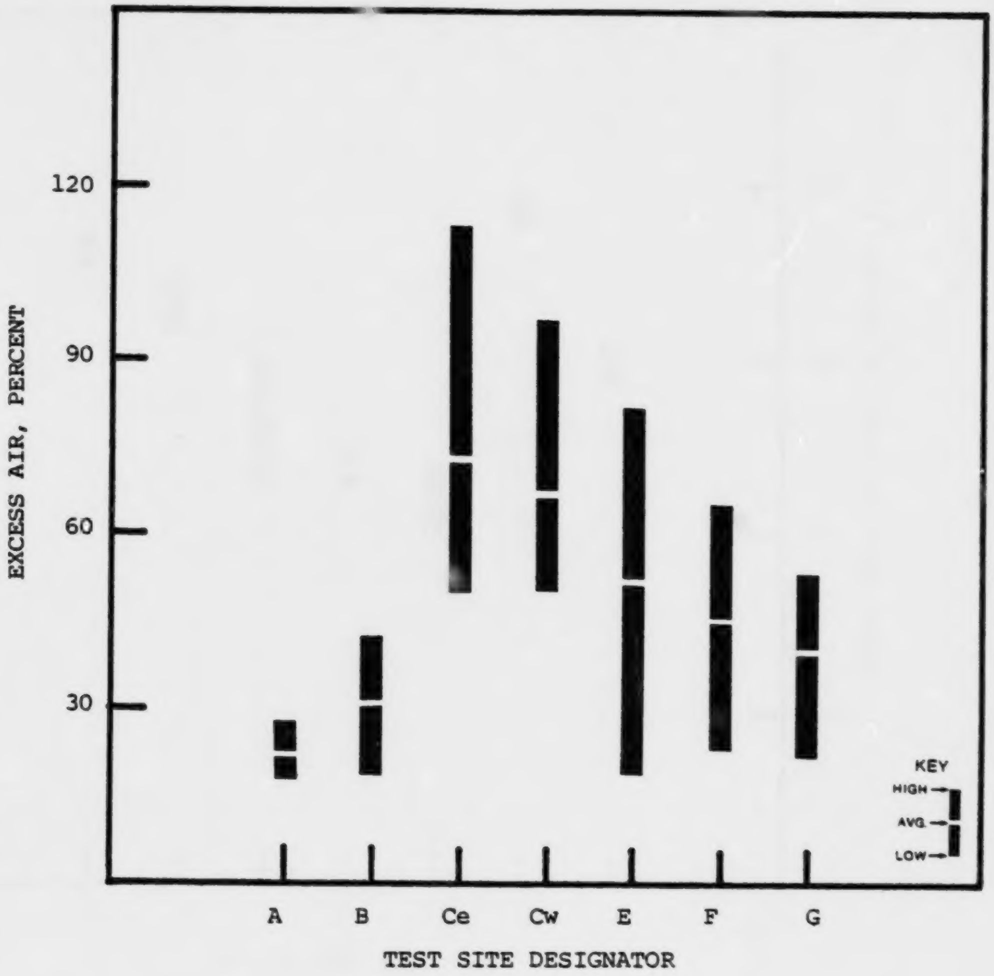

Figure 3-8. Excess Air Operating Levels of Six Spreader Stokers Fired at Full Load.

The ranges of excess air shown here are those at which emissions tests were conducted at full load. The lower end of the range indicates the point at which undesirable combustion conditions were encountered. All but Test Site C were successfully operated at the excess air levels stated in their design performance statements. At Test Site C, the inability to operate below 50% excess air without smoking was due at least in part to a stratified coal bed. Coal fines were much higher at some feeders than others, and the bed depth was uneven. It is also noted that Site C had a relatively low design grate heat release and this may have contributed to its higher excess air operating level. The design excess air levels for these stokers were: A-25%, B-31%, C-32%, E-30%, F-37% and G-31%.

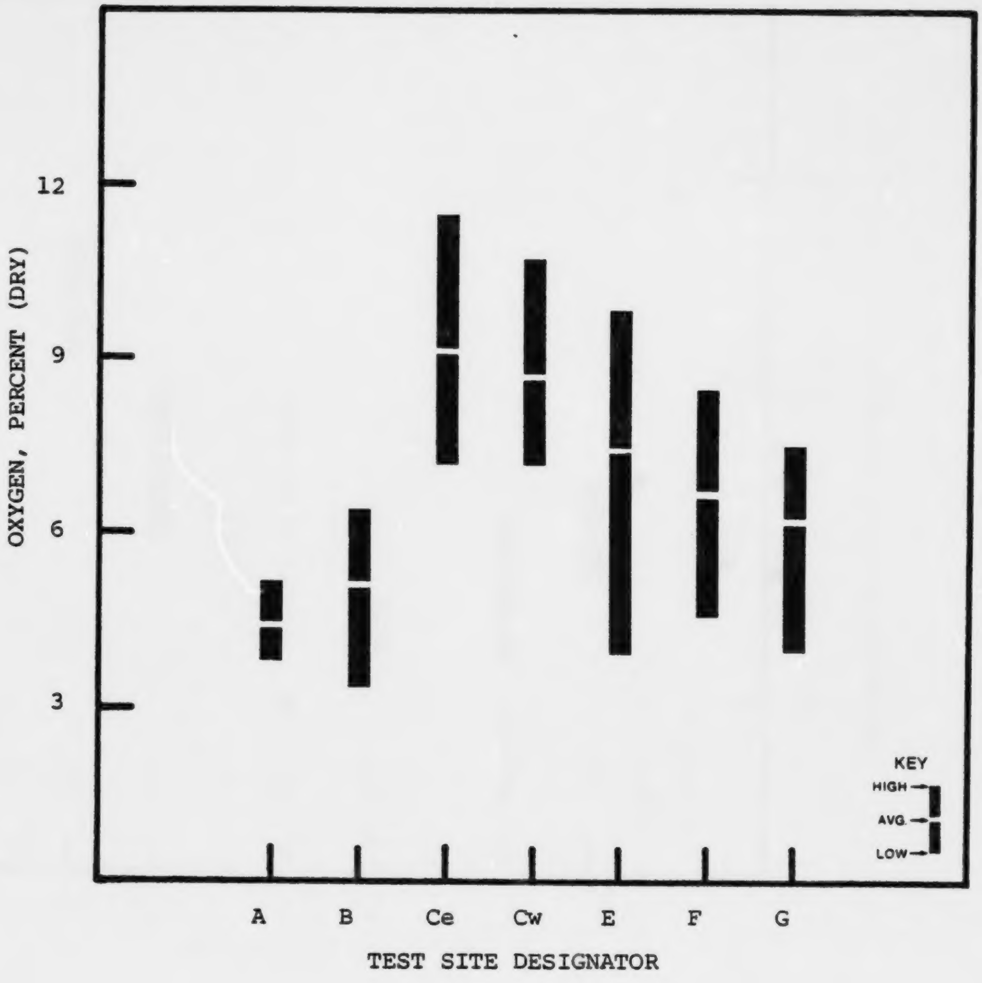

Figure 3-9. Excess Oxygen Operating Levels of Six Spreader Stokers Fired at Full Load.

The same comments apply to flue gas oxygen as do to excess air. For comparative purposes, it may be noted that thirty percent excess air is approximately equivalent to five percent oxygen. The data above are presented on a dry basis. Measurement was made of a multipoint sample collected at the boiler outlet using a fuel cell type oxygen analyzer.

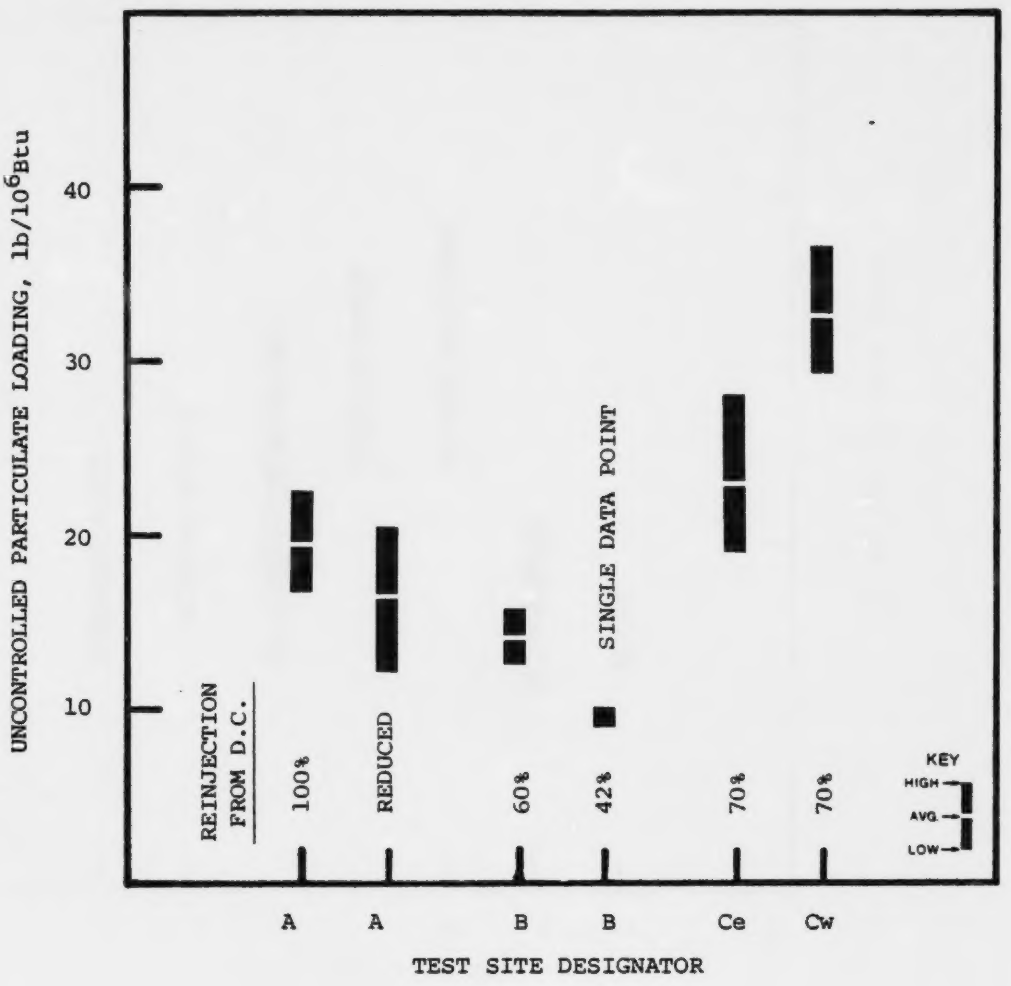

Figure 3-10. Uncontrolled Particulate Loadings for Three Spreader Stokers Fired at Full Load with Flyash Reinjection from the Mechanical Collector.

These particulate loadings represent tests in which a portion of the mechanical dust collector catch was reinjected to the furnace. At Site A, three tests were conducted with 100% reinjection from the dust collector, while the remaining tests were conducted with the reinjection rate reduced by an unknown amount. Sites B and C had selective type dust collectors which were designed to reinject 60% and 70%, respectively, of the collected ash. The actual percentage reinjected was not measured. During one test at Site B the reinjection rate was reduced to an estimated 42%. The uncontrolled particulate loadings in these tests ranged from 9.6 to 36.4 lb/10^6Btu. They were measured using EPA Method 5 equipment and procedures.

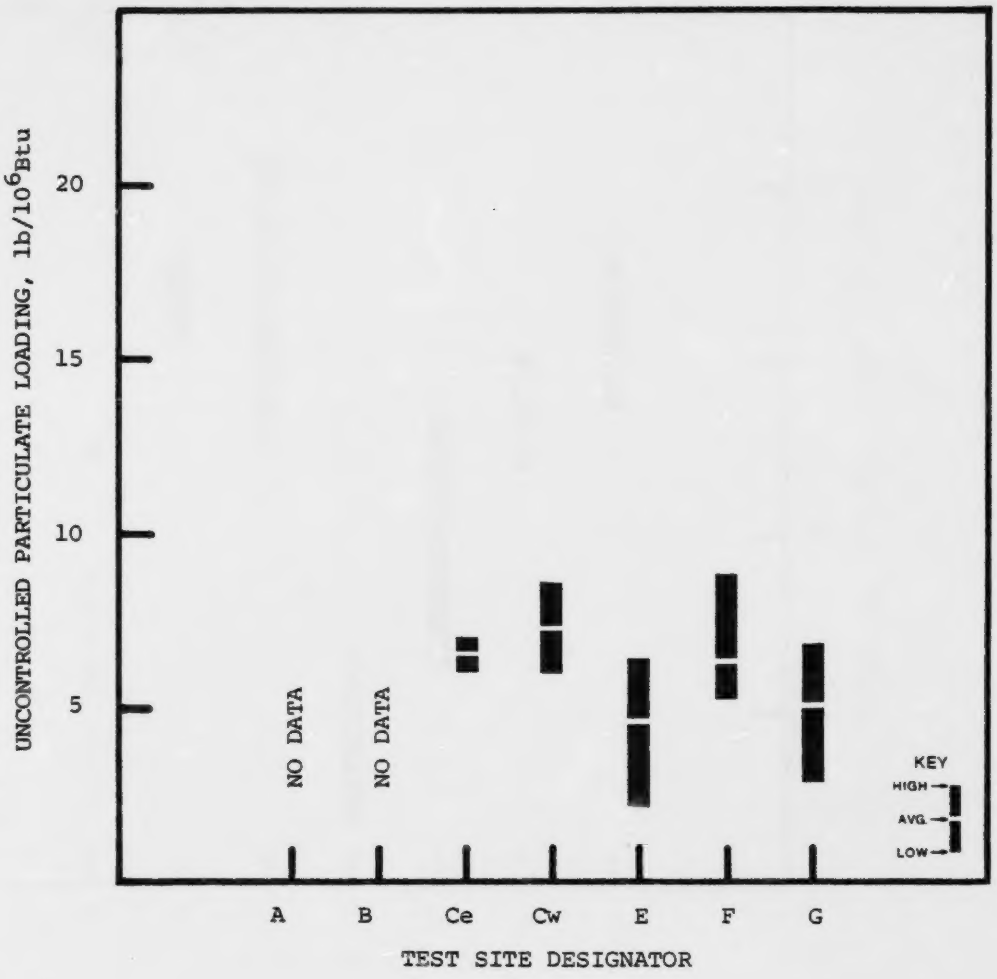

Figure 3-11. Uncontrolled Particulate Loadings of Four Spreader Stokers Fired at Full Load without Flyash Reinjection from the Mechanical Collector.

Without flyash reinjection from the mechanical collector the uncontrolled particulate data ranged from 2.1 to 8.8 lb/10^6Btu. Note that Test Site C was operated both with (Figure 3-10) and without (Figure 3-11) flyash reinjection from the mechanical collector and had very different particulate loadings under the two conditions. This illustrates that a portion of the reinjected flyash is reentrained in the gas stream and is resulting in increased particulate loadings. These boilers had some degree of flyash reinjection from the boiler hopper, and at Site F from the economizer hopper. The amount of flyash reinjected depends on duct geometry and whether or not the boiler is equipped with baffles. In most cases, the actual rate of reinjection was not known.

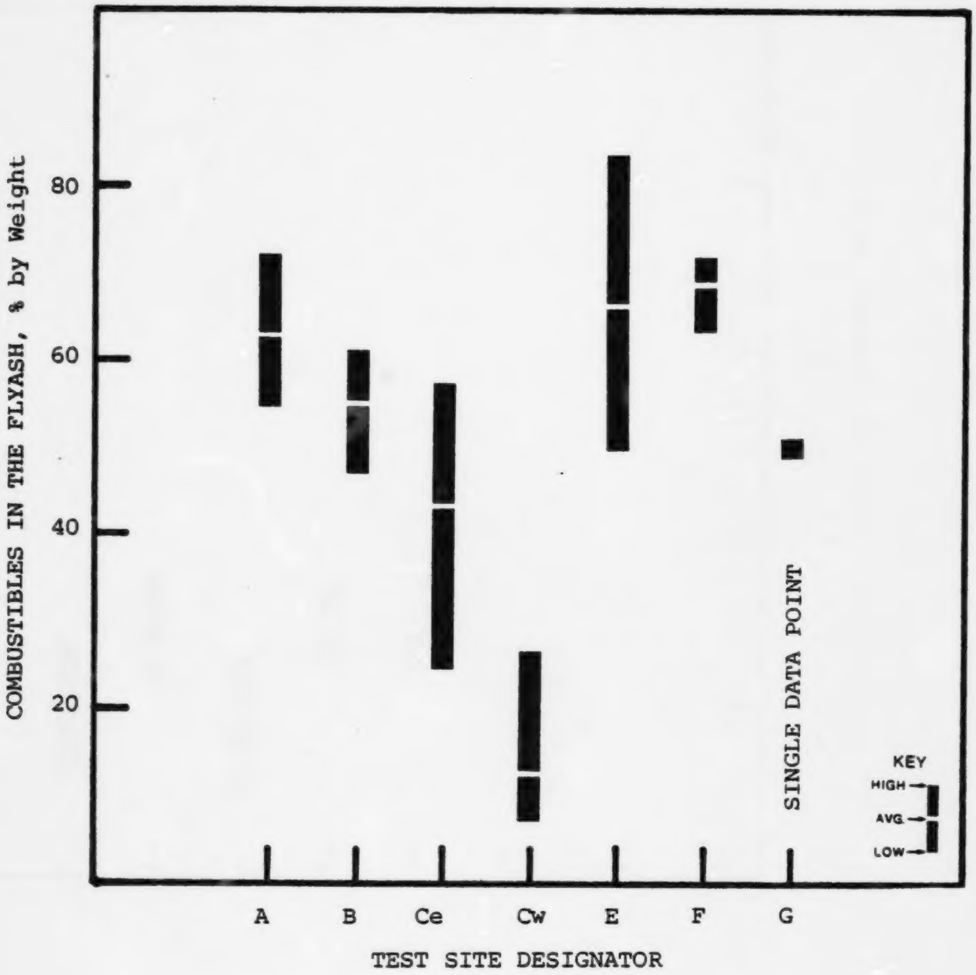

Figure 3-12. Percentage of Combustible Material in the Boiler Outlet Flyash of Six Spreader Stokers Fired at Full Load.

Most of the flyash samples collected during the particulate loading tests were analyzed for total combustible content. The data from Sites A, B, E, F and G show that combustible content ranged from 47% to 84%. At Site C, combustibles were as low as 24% on the Eastern bituminous coal (Ce) and 7% on the Western sub-bituminous coal (Cw). Factors contributing to Site C's low combustible levels might be its low grate heat release rate and high excess air operating levels. However, such a correlation is not supported by data from the other test sites.

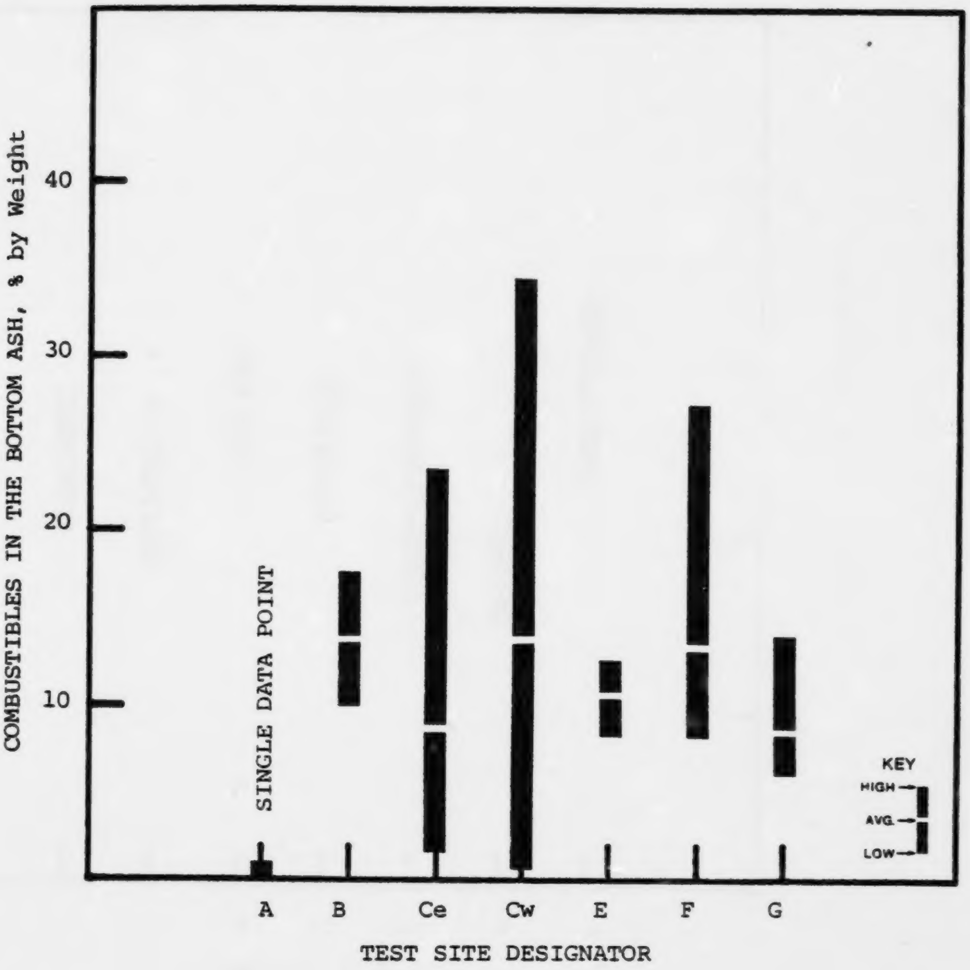

Figure 3-13. Percentage of Combustible Material in the Bottom Ash of Six Spreader Stokers Fired at Full Load.

Bottom ash samples were obtained in several increments at the dumping end of the grate or from the ash pit. The combustible content of these samples ranged from 0% to 34%. The averages for Sites B, C, E, F and G were relatively constant, ranging from 9 to 14%. For Site A, a single data point was obtained at full load indicating no combustibles.

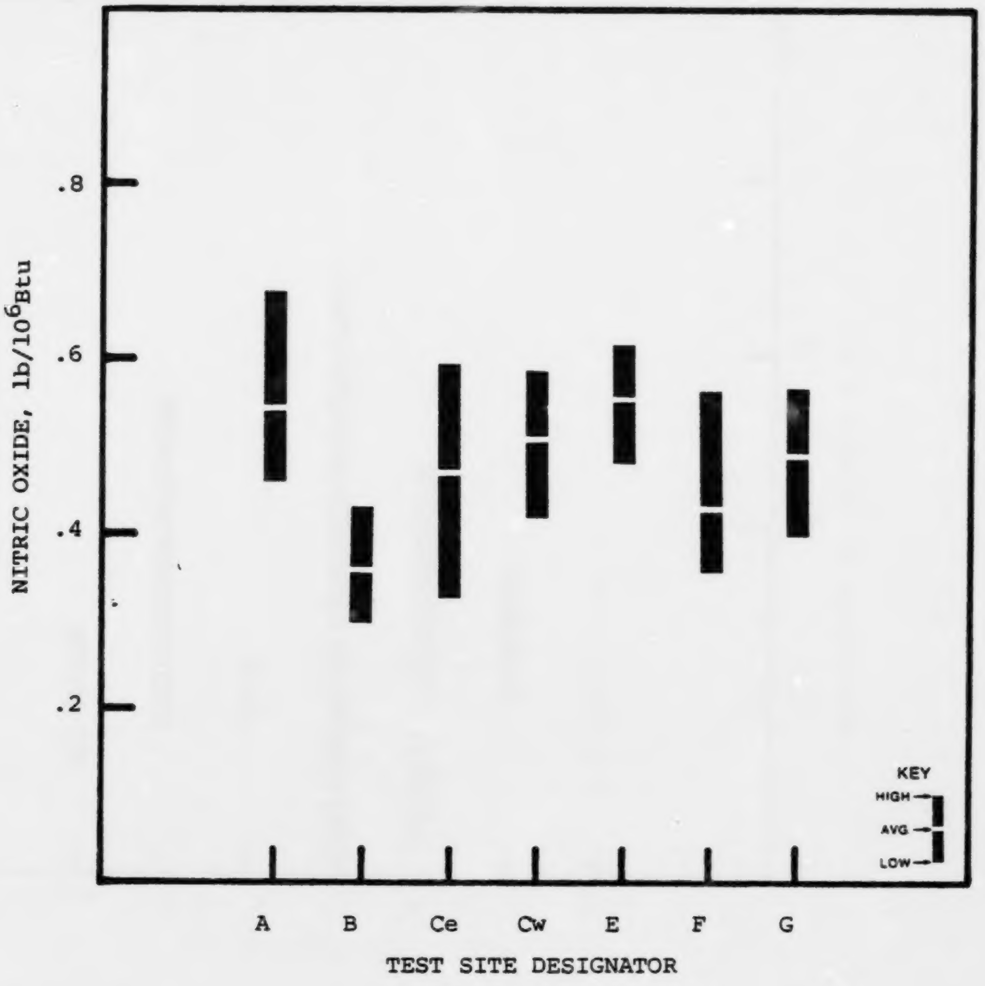

Figure 3-14. Nitric Oxide Emissions of Six Spreader Stokers Fired at Full Load.

Nitric oxide (NO) was measured at the boiler outlet using a chemiluminescent type analyzer. The NO data ranged from .30 to .68 lb/ 10^6Btu calculated as NO_2 when measured at full load. NO levels were found to be a function of excess air, heat release rate, and combustion temperature. Nitrogen dioxide (NO_2) did not exceed 4% of the total NOx and was most often negligible.

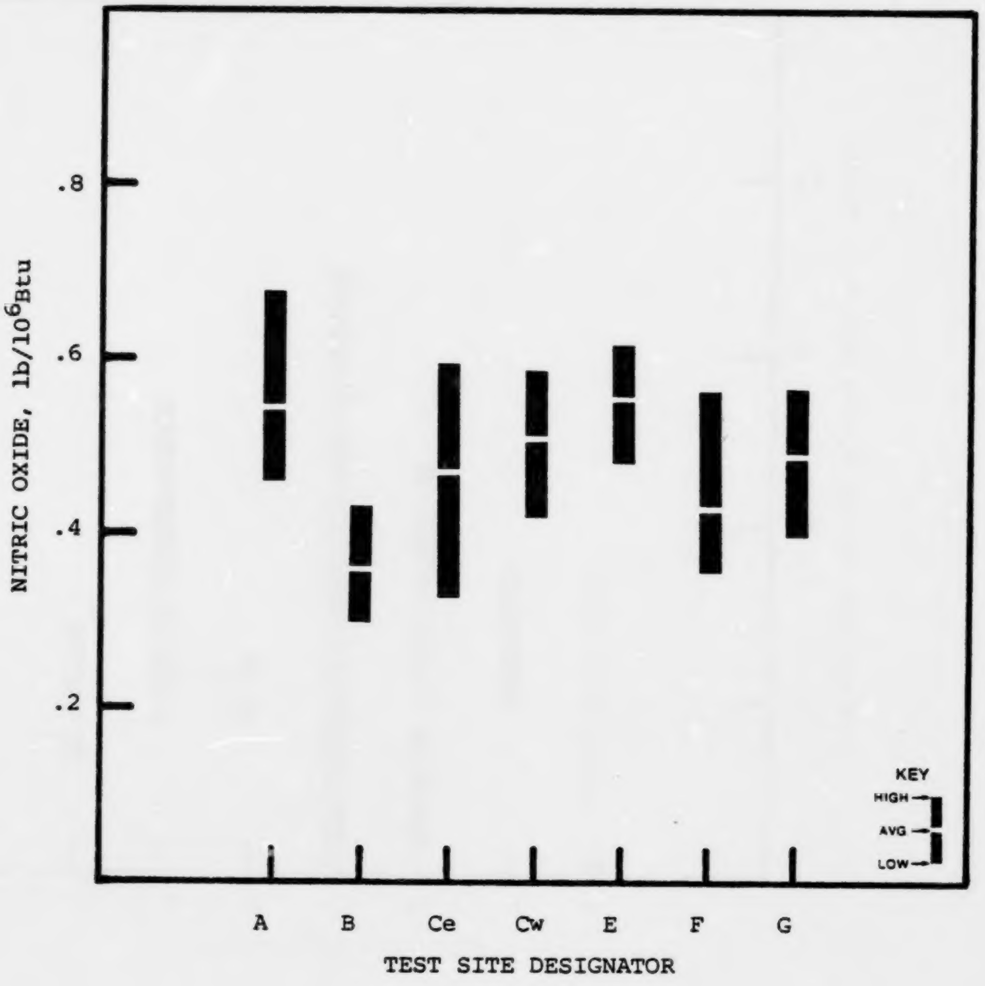

Figure 3-14. Nitric Oxide Emissions of Six Spreader Stokers Fired at Full Load.

Nitric oxide (NO) was measured at the boiler outlet using a chemiluminescent type analyzer. The NO data ranged from .30 to .68 lb/ 10^6Btu calculated as NO_2 when measured at full load. NO levels were found to be a function of excess air, heat release rate, and combustion temperature. Nitrogen dioxide (NO_2) did not exceed 4% of the total NOx and was most often negligible.

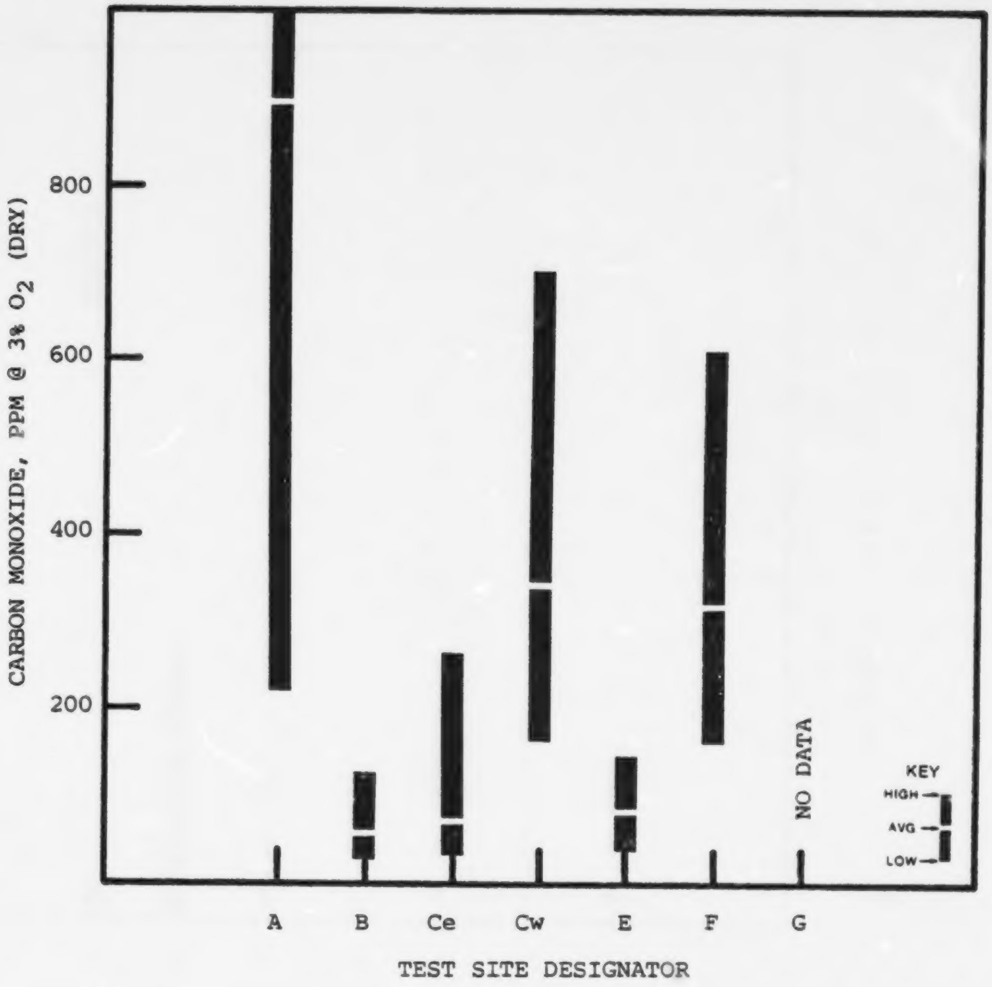

Figure 3-15. Carbon Monoxide Emissions of Five Spreader Stokers Fired at Full Load.

Carbon monoxide (CO) was measured at the boiler outlet of each unit with a non-dispersive infrared analyzer. This analyzer was out of service during testing at Site G. Carbon monoxide emissions were highest while burning low rank coals at Sites A and Cw. When excess air dropped below 30% at Site A, combustion conditions became unstable. This resulted in dramatic increases in carbon monoxide levels.

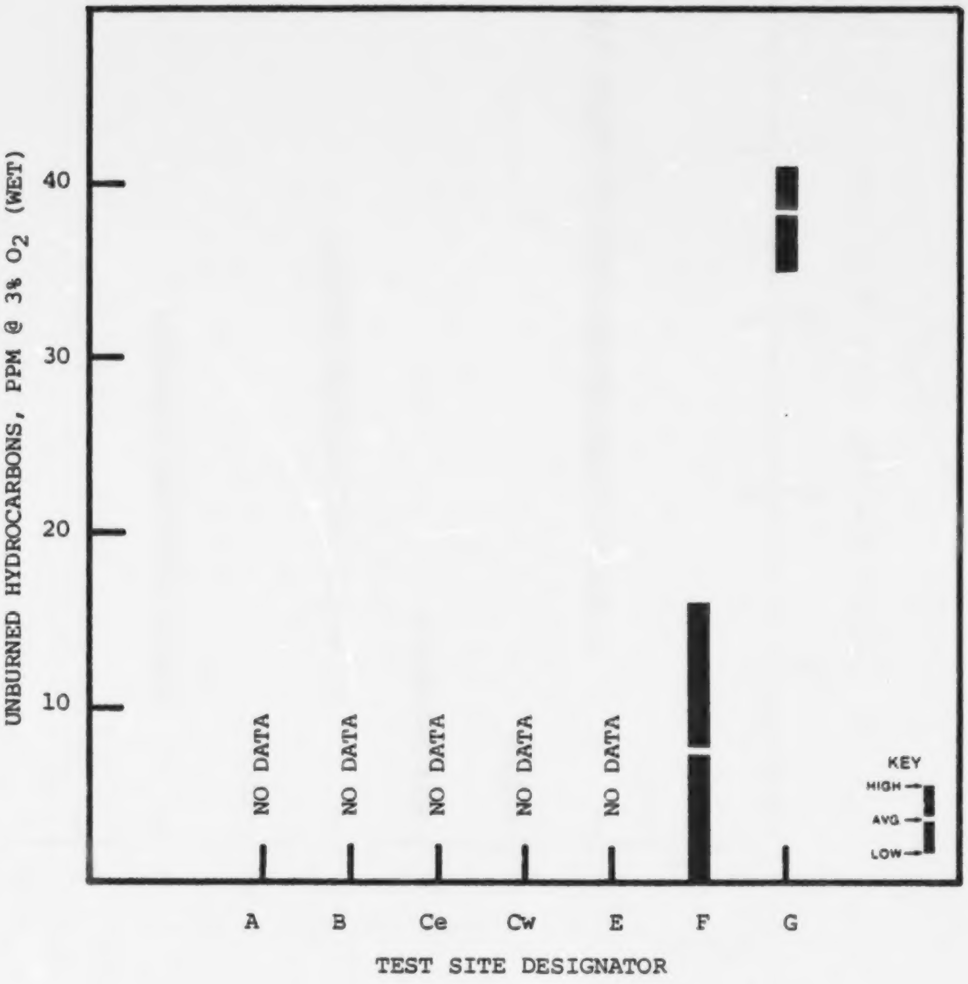

Figure 3-16. Unburned Hydrocarbon Emissions of Two Spreader Stokers Fired at Full Load.

Unburned hydrocarbons (HC) were measured at the boiler outlet of Sites F and G using a flame ionization type hydrocarbon analyzer. The gas samples were pulled through a heated teflon sample line. Unburned hydrocarbon levels ranged from 0 to 41 parts per million by volume (ppm) on a wet basis.

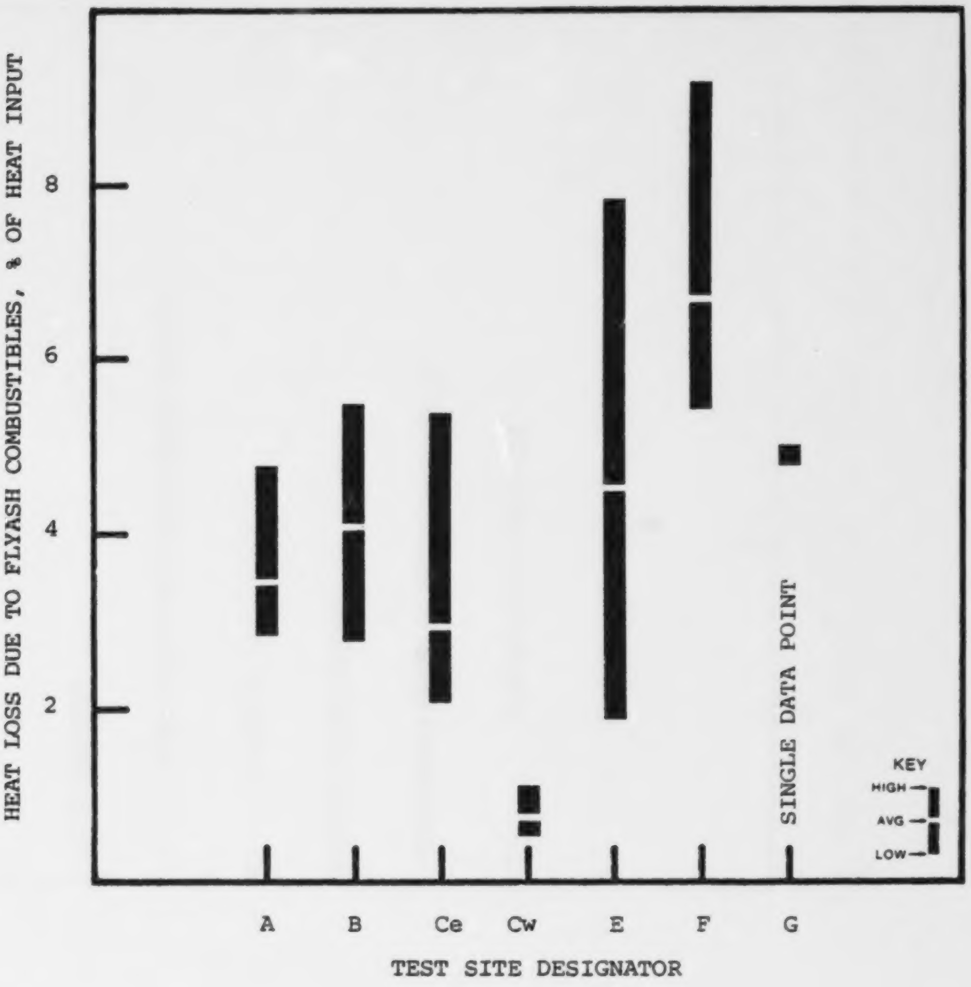

Figure 3-17. Heat Loss Due to Combustibles in the Flyash of Six Spreader Stokers Fired at Full Load.

The Flyash was not directly Analyzed for its Heating Value.

The heat loss due to combustibles in the flyash was computed by assuming a heating value of 14,250 Btu/lb in the combustible fraction of the flyash. Based on this assumption, heat losses ranged from 2% to 9% at all but Site Cw, where such losses ranged from .5 to 1.1%.

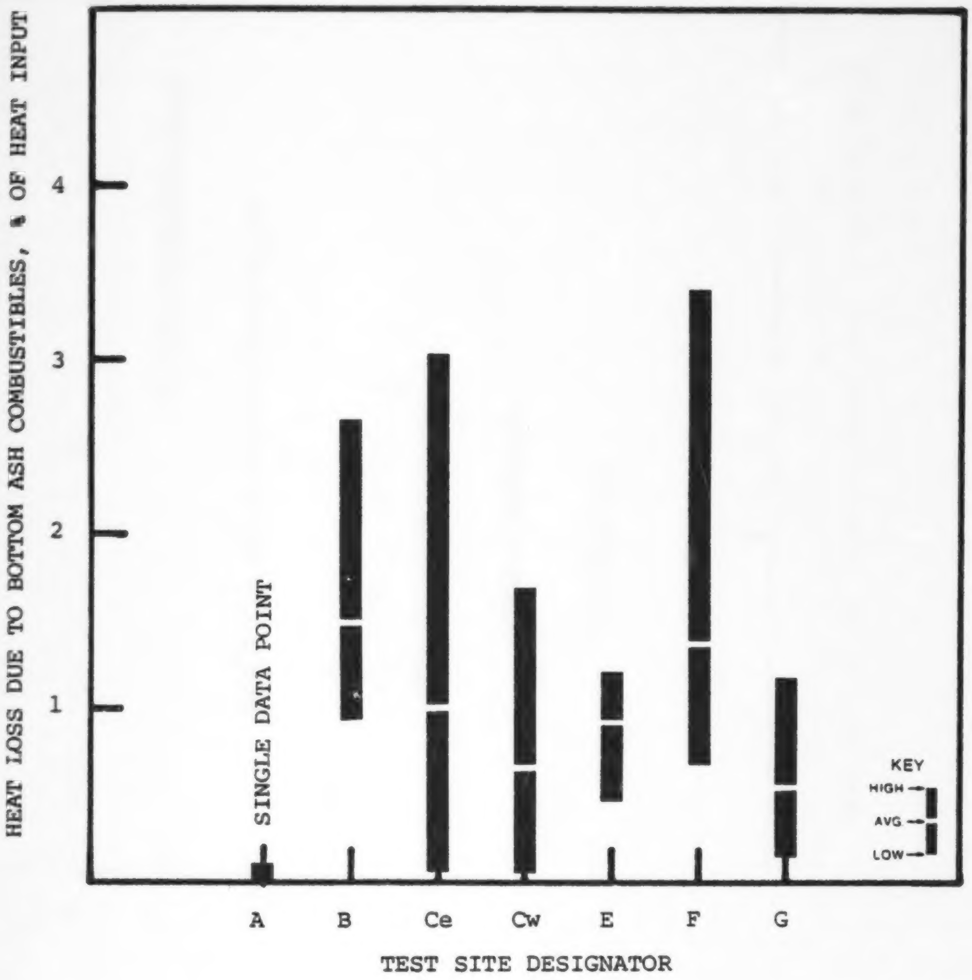

Figure 3-18. Heat Loss Due to Combustibles in the Bottom Ash of Six Spreader Stokers Fired at Full Load.

The Bottom Ash was not Directly Analyzed for its Heating Value.

The heat loss due to combustibles in the bottom ash was computed by assuming a heating value of 14,250 Btu/lb in the combustible material. The bottom ash flow rate was computed from a mass balance involving coal flow, percent coal ash, and particulate loading corrected for its combustible content. Calculated in this manner, heat losses ranged from negligible to 3.4%. The averages for Sites B, C, E, F and G ranged from .54% to 1.48%.

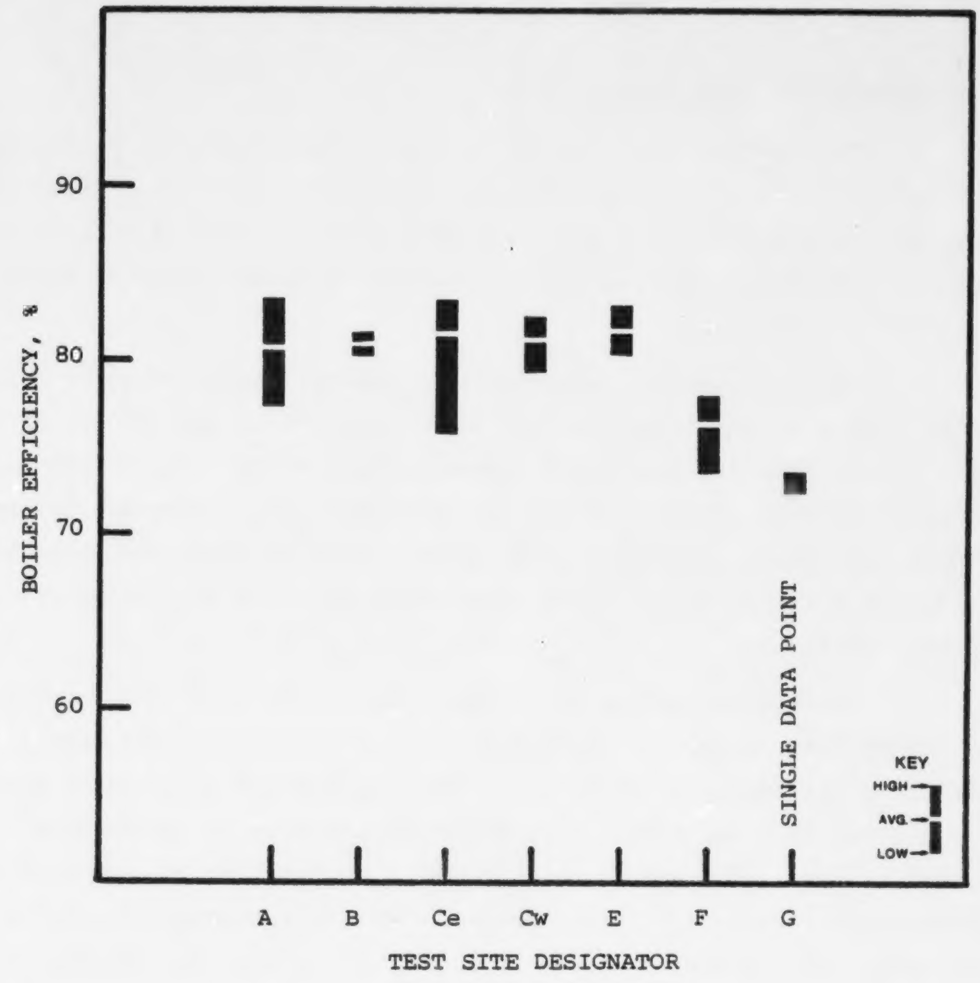

Figure 3-19. Boiler Efficiency of Six Spreader Stokers Fired at Full Load.

Boiler efficiency was determined by the heat loss method using the ASME Abbreviated Efficiency Test (PTC 4.1). At full load, the boiler efficiencies ranged from 73.0% to 83.4%. The lowest efficiency belongs to Site G, the only site which did not have either an air heater or an economizer. The design efficiencies of these units were: A-83.68%, B-84.16%, Cw-81.40%, E-80.41%, F-83.10% and G-77.04%.

3.3 RESPONSE TO HEAT RELEASE RATE

This section profiles the emissions and efficiency of six spreader stokers as a function of heat release rate. Four measures of heat release rate are considered. They are grate heat release, front foot heat release, furnace liberation, and percent of steaming capacity. Each of these will be briefly identified.

Heat release is the quantity of thermal energy above 70°F introduced into the furnace by the fuel each hour. It is the product of the hourly fuel rate and the fuel's higher heating value. Two of the six spreader stokers, Sites A and G, were not equipped with coal scales for determining hourly fuel rate. Therefore, heat release rate on these two units was taken to be the enthalpy of the steam times the steam flow divided by the fractional boiler efficiency.

Grate heat release is the most frequently used heat release rate in the following discussion. It is defined as the heat release per square foot of effective air admitting grate area, and is presented in units of Btu/hr-ft^2. For a given coal and excess air, grate heat release is proportional to the upward velocity of gases in the furnace. The American Boiler Manufacturers Association (ABMA) in its recommendation for stoker applications for bituminous coal suggests that the maximum grate heat release for spreader stokers with traveling grates not exceed 750,000 Btu/hr-ft^2.

Front foot heat release is the heat release per foot of grate width. Its maximum value for these stokers ranged from 9,000,000 to 14,500,000 Btu/hr-ft.

Volumetric heat release, commonly called furnace liberation, is the heat release per cubic foot of furnace volume. As such, furnace liberation is proportional to the residence time of gases in a furnace for a given coal and heat release rate. That is to say that two stoker boilers firing the same coal at the same furnace liberation and excess air would have similar furnace residence times. The six spreader stokers tested had maximum volumetric heat release rates ranging from 20,400 to 24,000 Btu/hr-ft^3.

Some of the data in this section are presented in terms of load, or percent of design steaming capacity. Load and heat release rate are proportional to each other on each unit to the extent that boiler efficiency is a constant.

Table 3-11 presents the design heat release rates for the six spreader stokers. Their differences reflect differences in unit design. One aim of the analysis presented below is to examine what, if any, relationship exists between these design differences and the unit's emissions and efficiency. The other aim of this section is to profile the emissions and efficiency as the heat release rate is changed on a given unit. The results are presented on an emission-by-emission basis in the following subsections.

TABLE 3-11

DESIGN HEAT RELEASE RATES

	Furnace Liberation $Btu/hr\text{-}ft^3$	Grate Heat Release $Btu/hr\text{-}ft^2$	Front Foot Heat Release Btu/hr-ft
Site A	21,500	696,000	13,200,000
Site B	20,400	713,000	13,200,000
Site C	20,600	483,000	9,200,000
Site E	22,600	674,000	14,500,000
Site F	23,500	688,000	9,000,000
Site G	24,000	712,000	10,100,000

3.3.1 Excess Air vs Heat Release Rate

The excess air requirement is greater at lower loads than at full load in stoker boilers. Although this fact is well known, it is worthwhile documenting the magnitude of this relationship.

An example of this relationship is shown in Figure 3-20, which presents Site B data. In this example, a line has been drawn through the data representing the as-found or normal excess air operating profile for this unit.

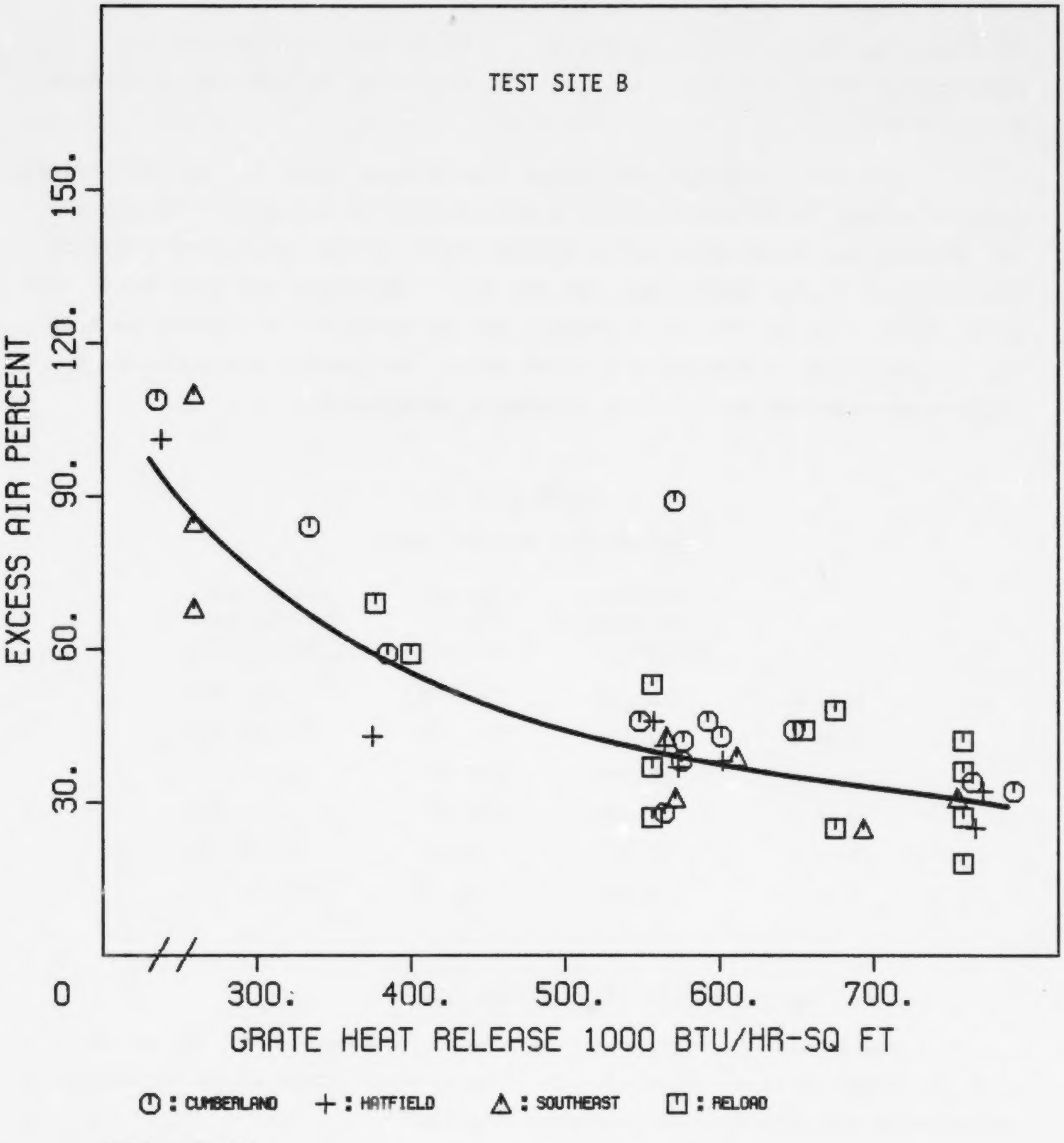

FIG. 3-20
EXCESS AIR VS. GRATE HEAT RELEASE

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A composite picture of the excess air profiles of six spreader stokers is shown in Figure 3-21. The slopes of the six curves are similar. However, there are considerable differences between the excess air requirements of the various units. These differences were found to relate to the physical size of the unit.

The excess air requirements at a grate heat release of 500,000 Btu/hr-ft^2 are plotted as a function of grate area in Figure 3-22. The relationship is clear, with the exception of Site C which will be discussed separately. The data could be plotted against other size parameters such as furnace width or furnace volume with similar results.

Two explanations for this relationship are suggested, both relating to the lower surface to volume ratio of the larger units. First, the larger units are likely to leak a smaller percentage of air through access doors, casings, and air seals. Second, the larger units are likely to release a smaller fraction of their heat to the furnace wall and thus have a more intense flame. Both explanations are only suggestions. Temperature and gaseous traverses immediately above the flame zone would be helpful in determining the magnitude of wall effects in stoker boilers.

As indicated in Figure 3-22, Site C had a higher excess air requirement for its size than did the other sites. This was the result of coal size stratification in the coal hoppers. A disproportionate fraction of the coal fines were being fed to one side of the stoker. This resulted in one side of the stoker operating at a lower excess air than the other. Since the excess air was limited by smoke and clinkering at the low side, the average excess air was higher than it should be. The lower limit of excess air on all of the stokers was indicated by excessive carbon monoxide, smoke or clinkering on the grate.

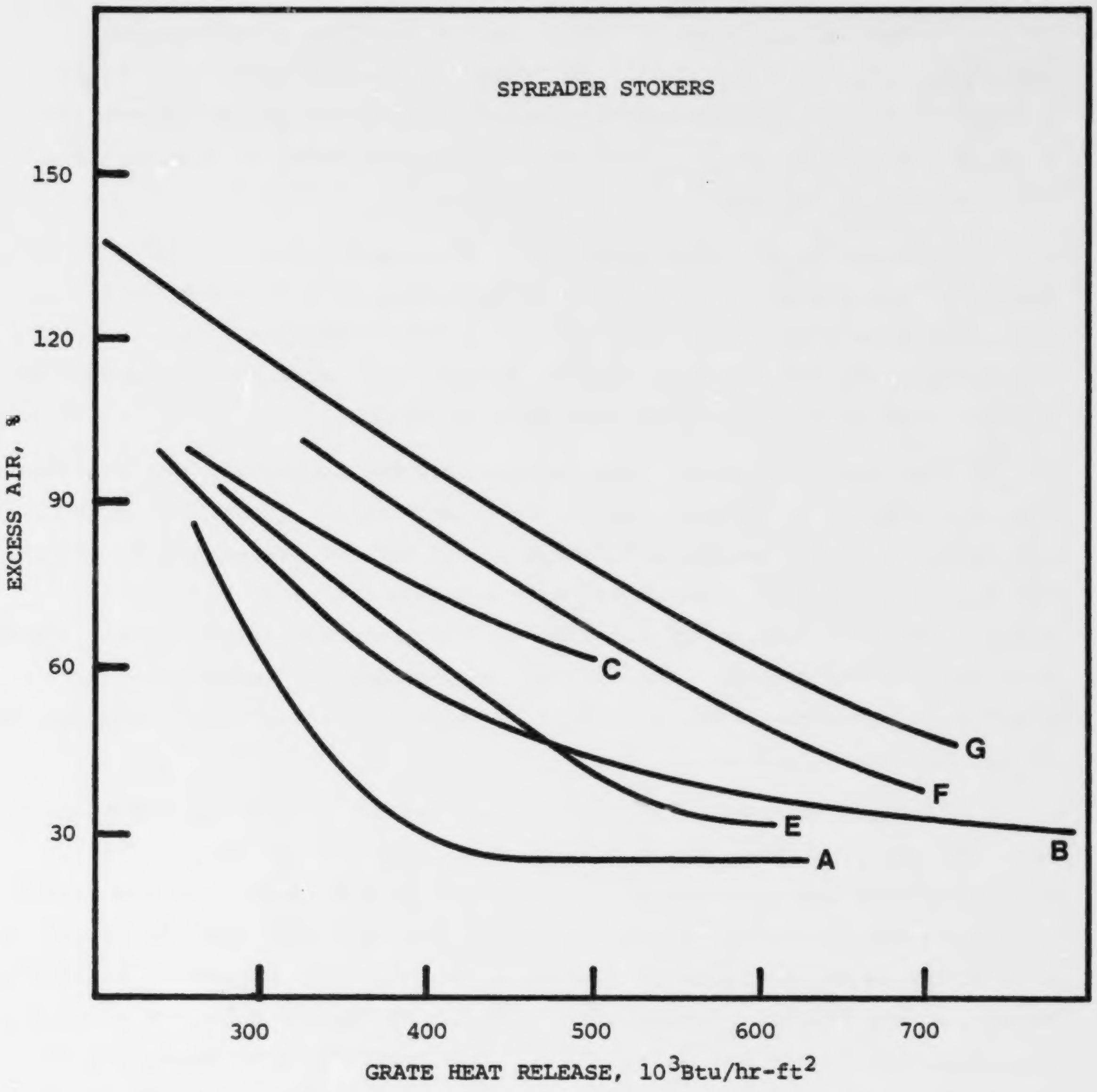

Figure 3-21. Excess Air Profiles for Six Spreader Stokers Representing Normal Operating Conditions.

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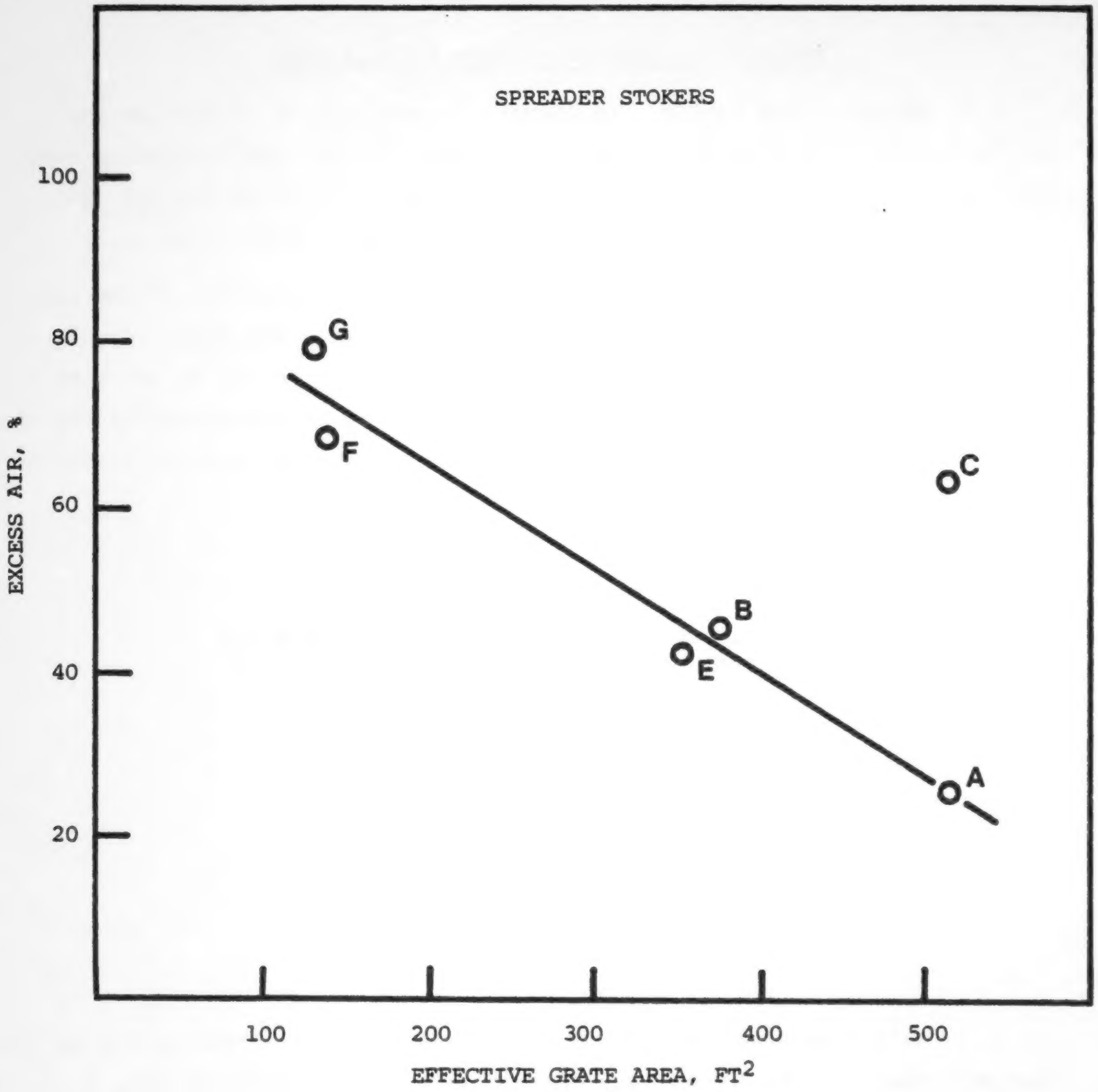

Figure 3-22. Excess Air Operating Levels of Six Spreader Stokers Showing a Correlation with Size of Grate. The Data Represents a Grate Heat Release Rate of 500,000 Btu/hr-ft^2.

3.3.2 Particulate Loading vs Heat Release Rate

Uncontrolled particulate loading -- particulate loading at the boiler outlet -- was found to increase as heat release rate increased over its full range. The rate of increase was roughly linear in four of the units, but accelerated as full load was approached at Sites C and F.

Figure 3-23 presents the particulate loading profiles of the six spreader stokers as a function of grate heat release. The slope of this relationship is greatest for Sites A and C. This may be due to the high degree of flyash reinjection at these two sites, or to properties of the coal ash. The slope of this relationship was also examined by linear regression analysis. The results are given in Table 3-12.

TABLE 3-12

INCREASE IN UNCONTROLLED PARTICULATE LOADING FOR EACH 10^3BTU/HR-FT^2 GRATE AREA INCREASE

Site A	.0328 lb/10^6Btu
Site B	.0100 lb/10^6Btu
Site C	.0845 lb/10^6Btu
Site E	.0079 lb/10^6Btu
Site F	.0085 lb/10^6Btu
Site G	.0048 lb/10^6Btu

Test Site G was unique in that it was tested at loads as low as 16% of design capacity. The uncontrolled particulate loading data for Site G are plotted against grate heat release in Figure 3-24. This plot shows only the data obtained under steady load operation. Three swing load data points were removed for clarity. Uncontrolled particulate loading clearly increases as heat release rate increases.

Figure 3-25 shows the controlled particulate loading at Test Site G. The observed tendency for controlled particulate loading to increase as heat release rate increases in the upper 50% of its range was common to four of the spreader stokers. Two spreaders, Sites B and F, showed no change with heat release rate. Only Site G showed an extremely sharp increase in controlled

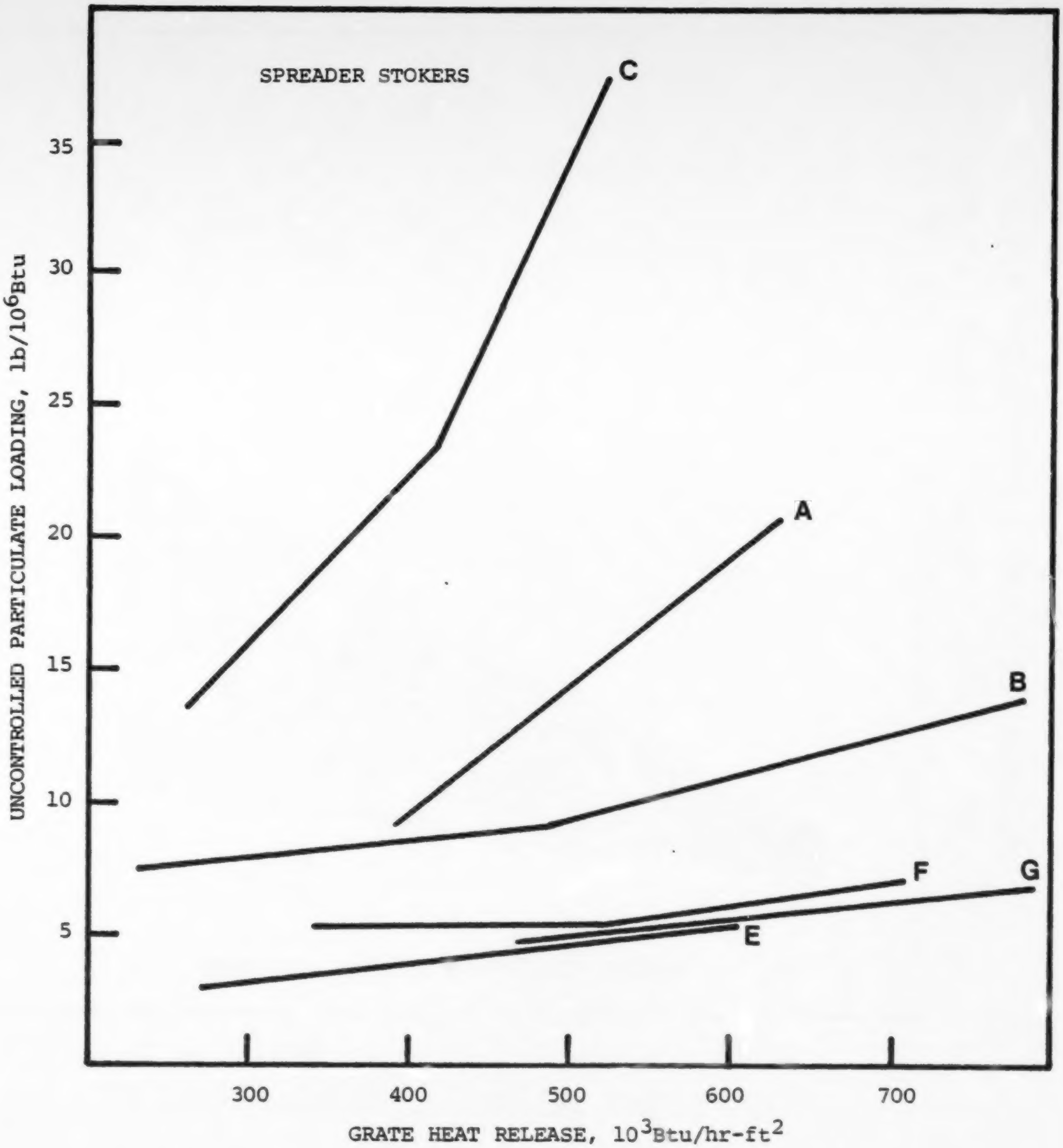

Figure 3-23. Uncontrolled Particulate Mass Loading Trends with Grate Heat Release for Six Spreader Stokers.

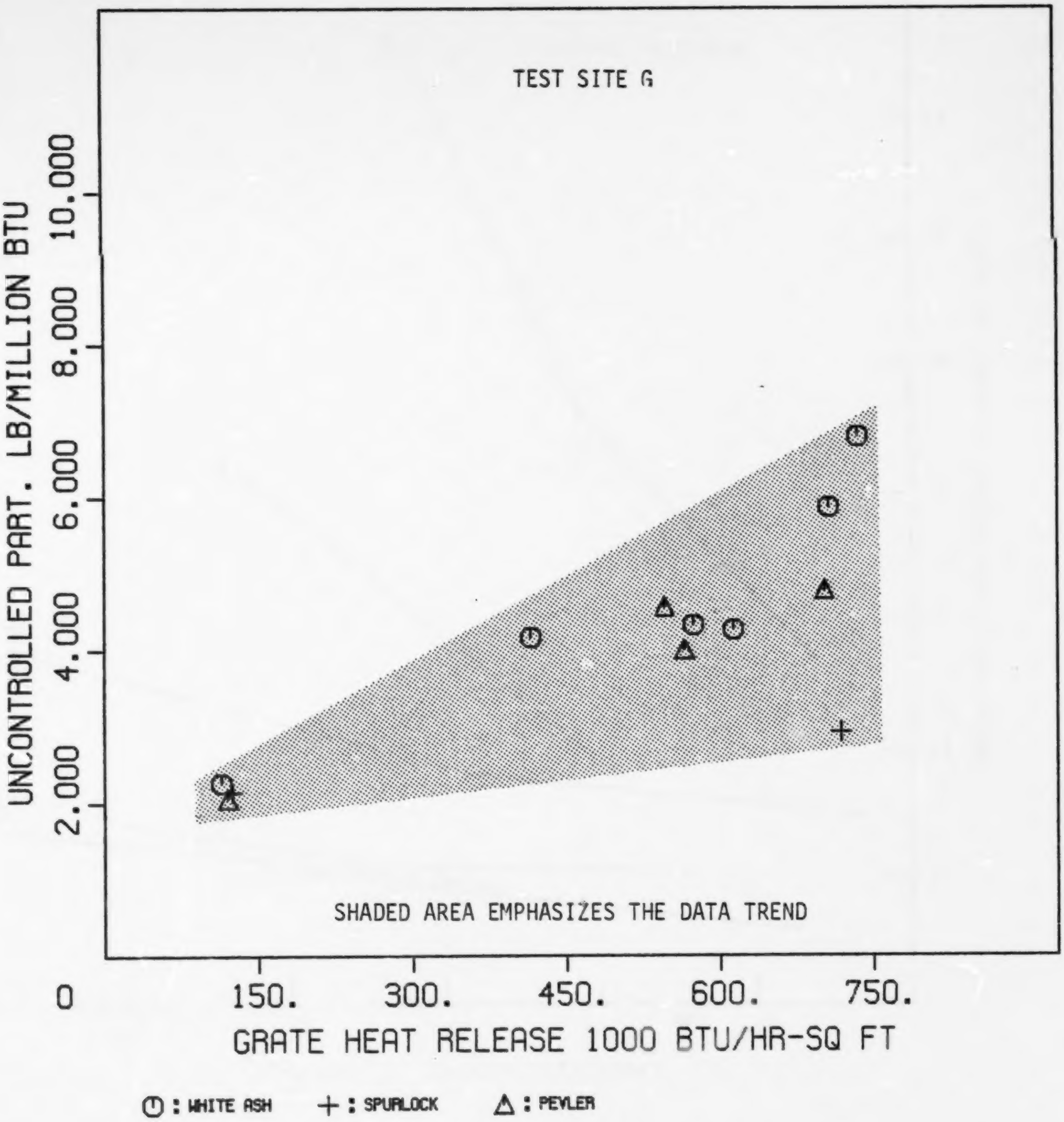

FIG. 3-24
UNCONTROLLED PART. VS. GRATE HEAT RELEASE

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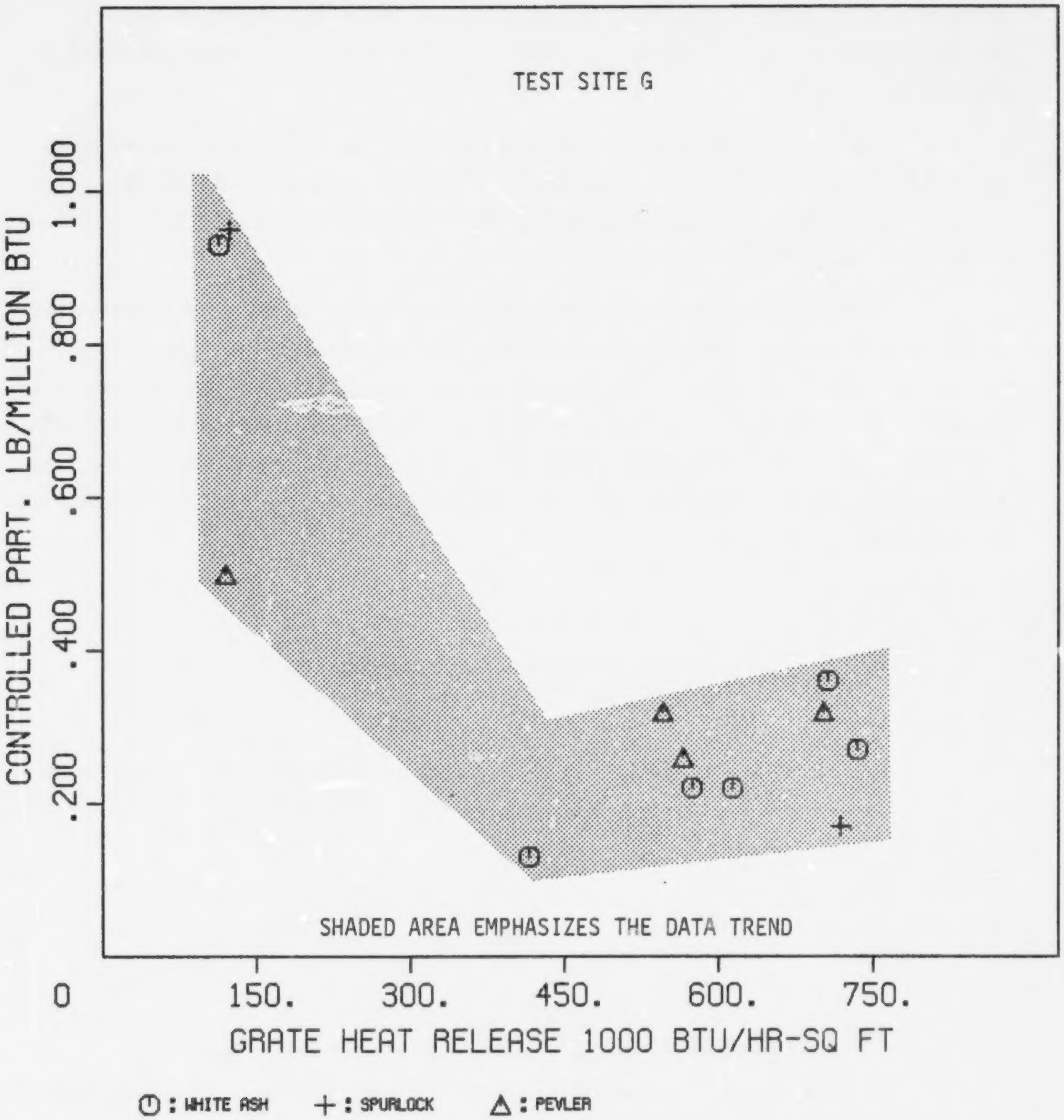

FIG. 3-25
CONTROLLED PART. VS. GRATE HEAT RELEASE

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particulate loading at low heat release rates. This was due to a drop in mechanical collector efficiency at the unusually low firing rate obtained at this site.

The effects of design heat release rates on full load uncontrolled particulate loading were also examined. It might be expected that units with higher design heat release rates would have higher uncontrolled particulate loadings. This was not the case.

Table 3-13 presents the data for those sites which were operated at their design steaming capacity and without flyash reinjection from their mechanical dust collector. The data show that the unit with the highest heat release rates, Site G, also had the lowest uncontrolled particulate loadings. The only conclusion to be drawn from these data is that uncontrolled particulate loading cannot be predicted from heat release rates alone. Other factors are involved.

TABLE 3-13

UNCONTROLLED PARTICULATE LOADING VS
DESIGN HEAT RELEASE RATES

	Range of Full Load Particulate Loading $lb/10^6Btu$	Furnace Liberation $10^3Btu/hr\text{-}ft^3$	Grate Heat Release $10^3Btu/hr\text{-}ft^2$	Front Foot Heat Release $10^6Btu/hr\text{-}ft$
Site C	6.0-8.6	20.6	483	9.2
Site F	5.2-8.8	23.5	688	9.0
Site G	2.9-6.8	24.0	712	10.1

3.3.3 Combustibles in the Flyash vs Heat Release Rate

In this report, combustibles in the flyash refers to the percentage by weight of combustible material in the flyash sampled at the boiler outlet.

Combustibles in the flyash tended to increase as heat release rate increased. This trend is shown in Figure 3-26 where the average flyash combustible level is plotted against grate heat release for each of the six spreader stokers.

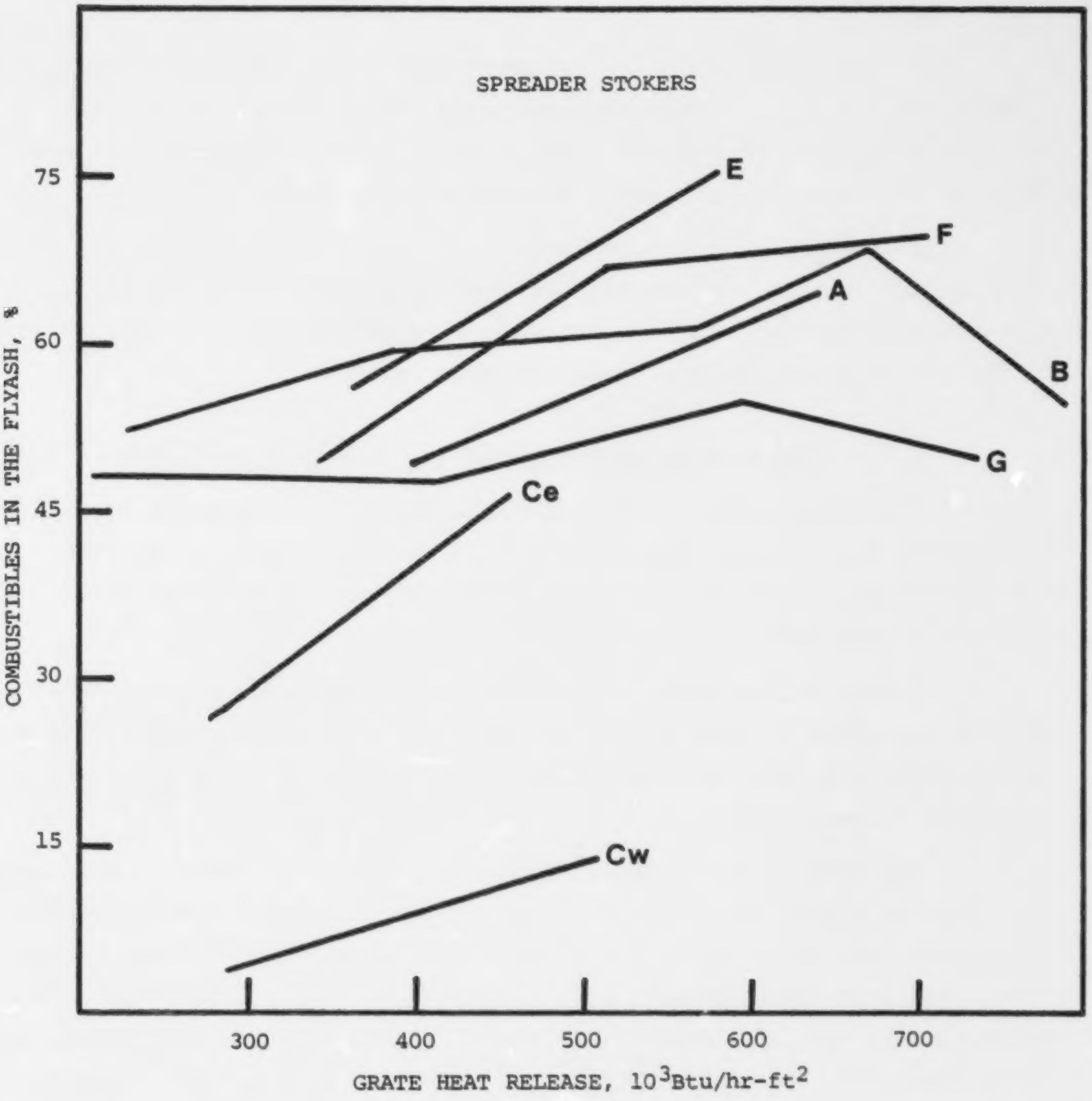

Figure 3-26. Flyash Combustible Profiles for Spreader Stokers as a Function of Grate Heat Release.

At high heat release rates, the flyash combustible levels appear to drop at Sites B and G. These apparent drops are not definite. The test data, shown in Figures 3-27 and 3-28 for Sites B and G, respectively, show that one or two stray data points could alter this trend.

The magnitude of the combustible vs load trend was highly variable, ranging from nothing to about 14% combustibles per 100,000 Btu/hr-ft^2 increase in grate heat release. It was difficult to establish trends at some sites due to data scatter and the many other variables involved.

3.3.4 Combustibles in the Bottom Ash vs Heat Release Rate

The percentage of combustible material in the bottom ash varied very little with heat release rate. A composite plot indicating the bottom ash combustible levels vs grate heat release for each site except Site C is shown in Figure 3-29.

Figure 3-30 presents bottom ash combustible data for a single site, in this case Site G. Even at the extremely low heat release rate of 150,000 Btu/hr-ft^2 grate area, the combustible level was similar to levels found at high heat release rates.

The data at Site C behaved differently than the others. These data are shown in Figure 3-31. While firing Eastern bituminous coals at Site C, the combustible level in the bottom ash showed considerable scatter. That is, three full load tests produced between 19 and 24% combustibles while eight others at the same load produced between 1 and 5%. While firing Western subbituminous coal, the combustibles increased as heat release rate decreased, reaching 50% at 300,000 Btu/hr-ft^2 grate area.

One can only speculate on the reasons for this anomalous behavior. Site C was unique in that it operated at very low grate heat release rates by design. Site C also had a problem with pancaking, or sheet clinkering on the surface of the fuel bed. The pancaking could explain the high and variable combustible levels in the bottom ash.

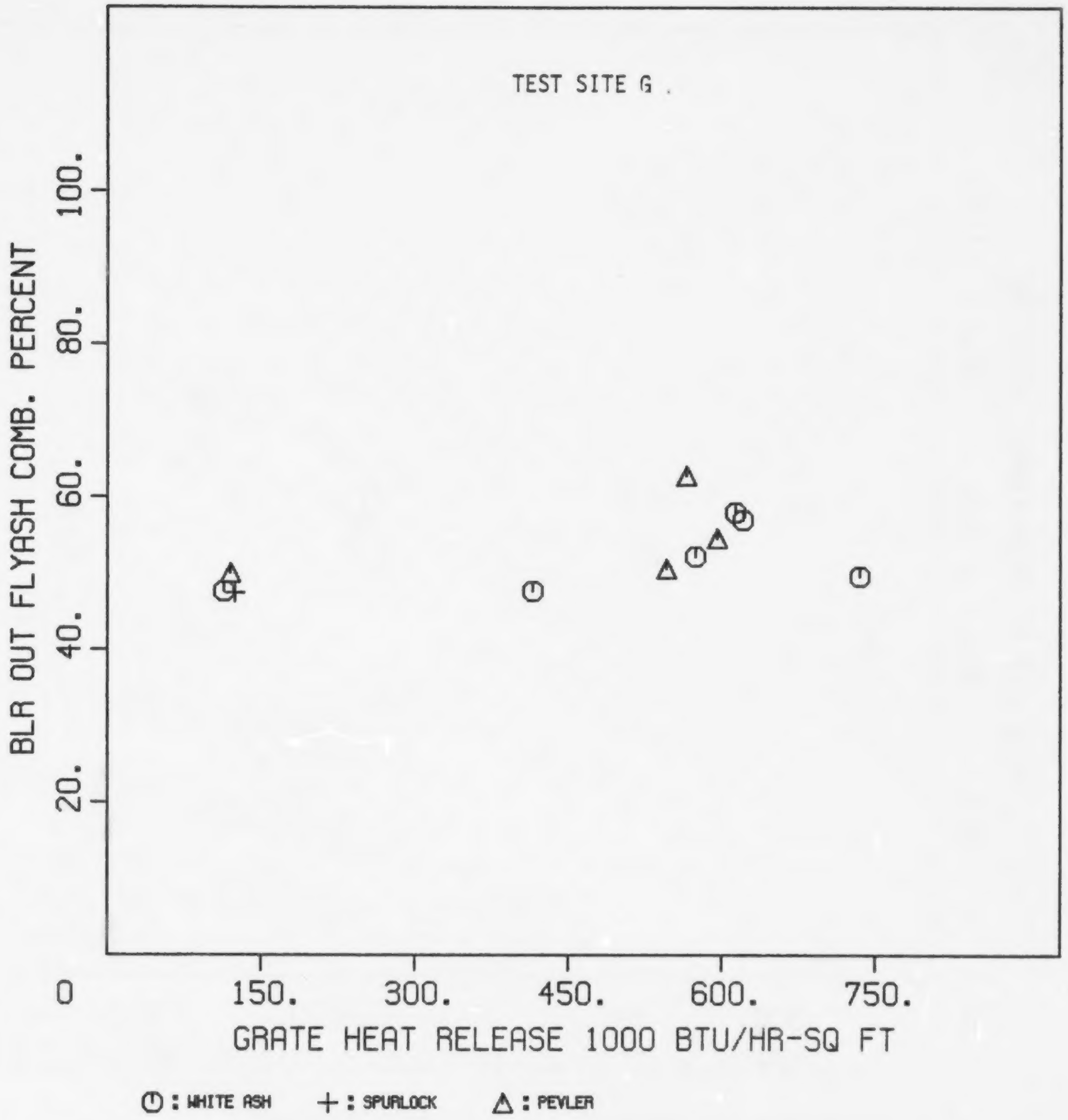

FIG. 3-27
BLR OUT FLYASH COMB. VS. GRATE HEAT RELEASE

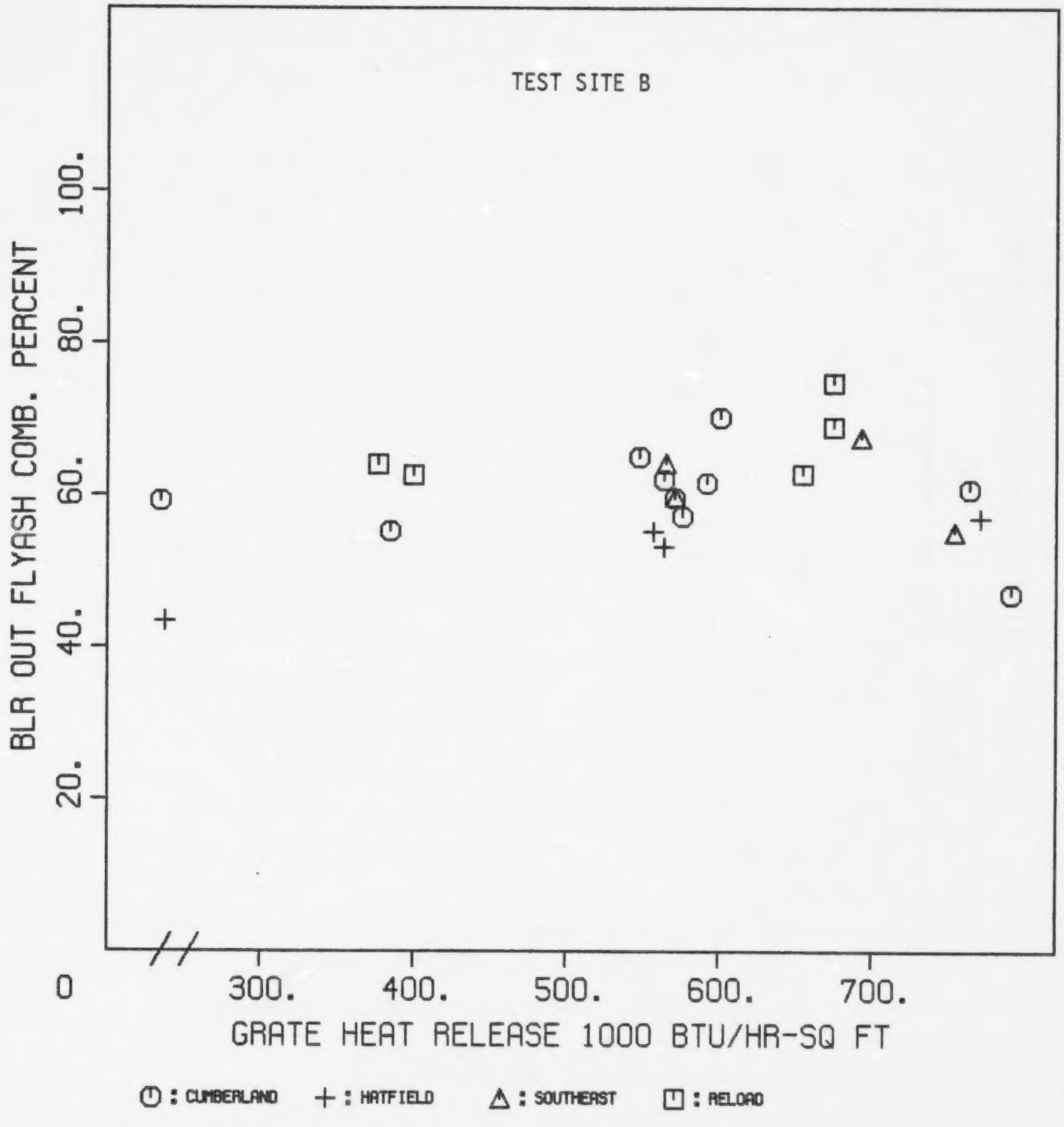

FIG. 3-28

BLR OUT FLYASH COMB. VS. GRATE HEAT RELEASE

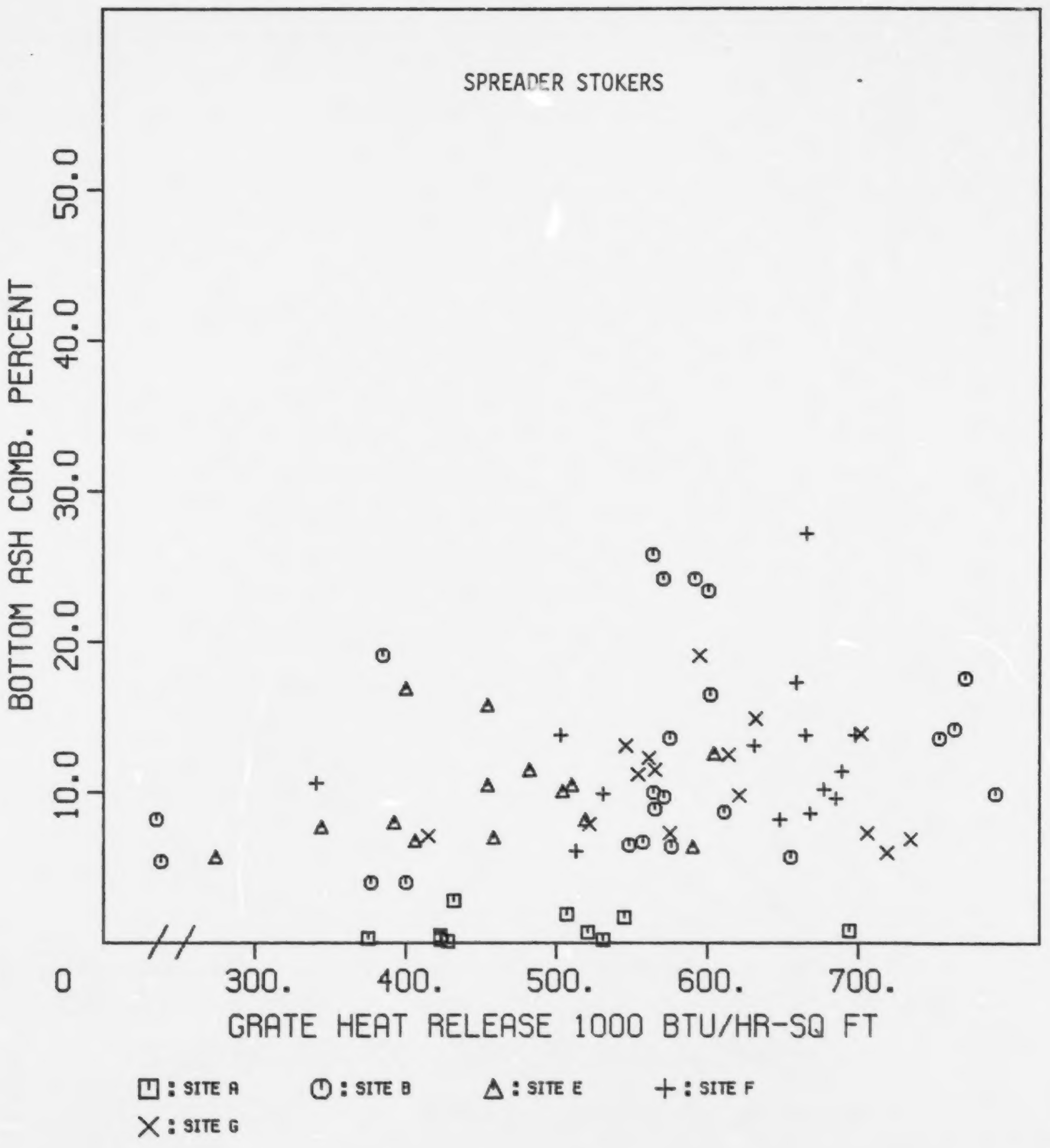

FIG. 3-29
BOTTOM ASH COMB. VS. GRATE HEAT RELEASE

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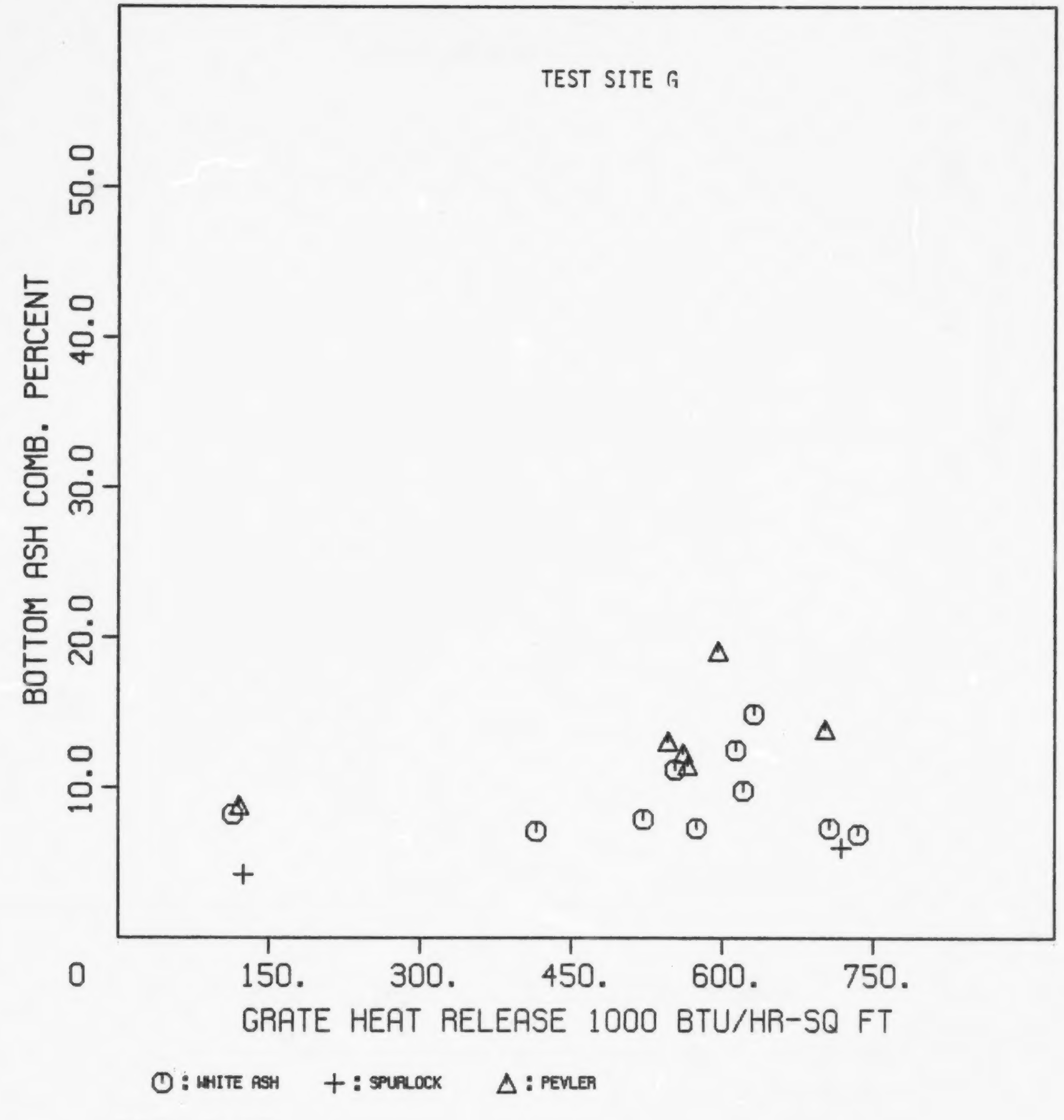

FIG. 3-30
BOTTOM ASH COMB. VS. GRATE HEAT RELEASE

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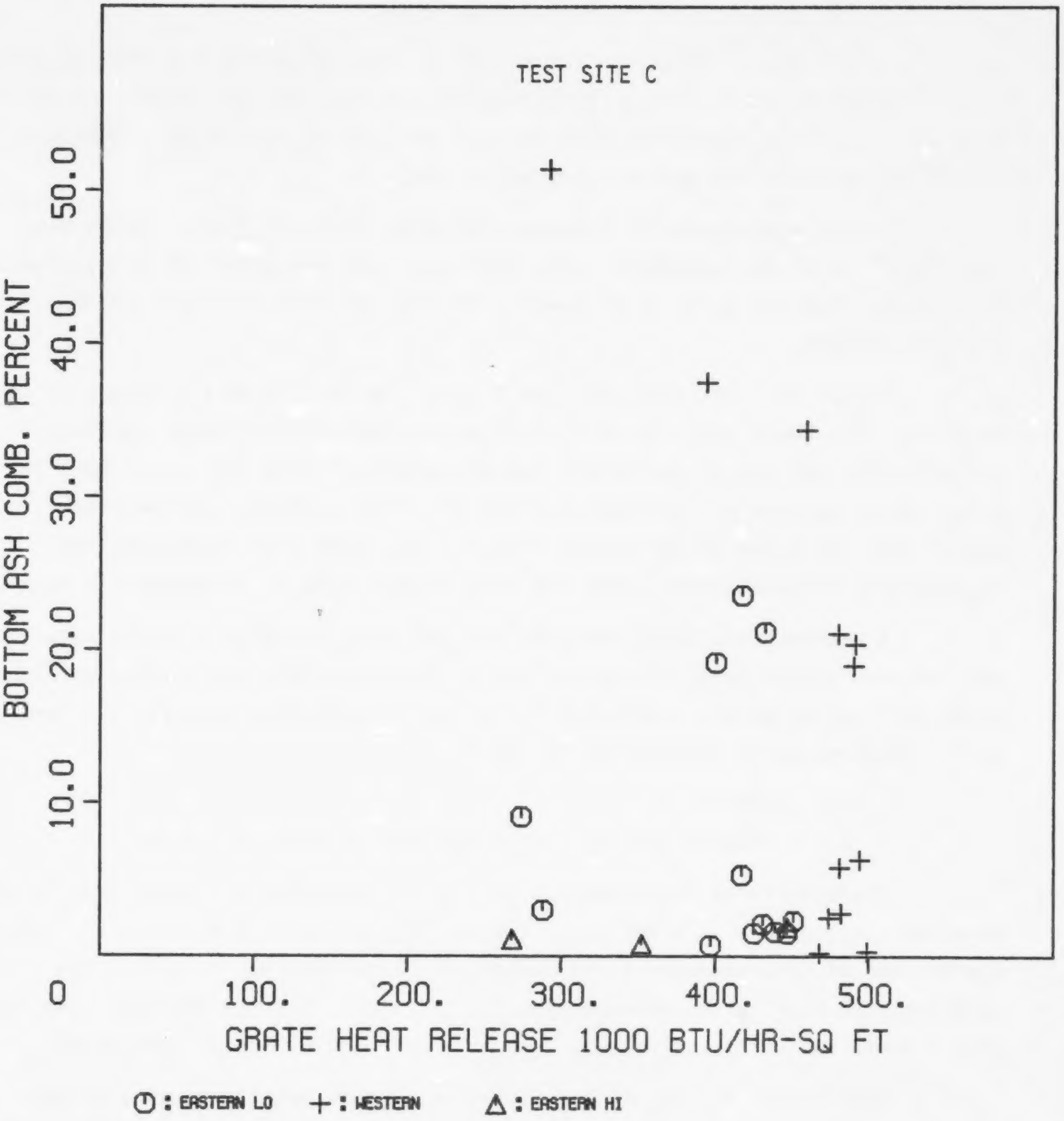

FIG. 3-31
BOTTOM ASH COMB. VS. GRATE HEAT RELEASE

3.3.5 Nitric Oxide vs Heat Release Rate

Nitric oxide levels are a function of both excess air and heat release rate in stoker boilers. Thus, it is necessary to sort out the effects of excess air before the effects of heat release rate can be determined. Multiple regression analysis was used to accomplish this.

Before presenting the computer analysis, the data from a single site, Test Site F, will be presented. Data from this site exhibited the relationships most clearly and can serve as an example for the behavior of nitric oxide in spreader stokers.

Figure 3-32 presents the Site F nitric oxide data as a function of excess air. All tests were run at three distinct heat release rates equivalent to 100%, 75%, and 50% of the unit's design capacity. This plot shows that the relationship between nitric oxide and excess air at constant load is roughly linear over the range of excess air tested. This plot also shows that the relationship between nitric oxide and heat release rate is approximately linear.

A mathematical model was made for each site assuming a linear relationship between nitric oxide and excess air at constant load, and between nitric oxide and load at constant excess air. Multiple regression analysis was used to fit the data to an equation of the form:

$$\text{NO, lb}/10^6\text{Btu} =$$
$$a + b\ (\text{Excess Air, \%}) + c\ (\text{Grate Heat Release, Btu/hr-ft}^2)$$

The results of this modeling effort are presented in Table 3-14. Along with the coefficients a, b and c, is the coefficient of determination R^2. The coefficient of determination gives a measure of how well the data fits the equation. If $R^2 = 1$, it was a perfect fit. The best fit was obtained with the Site F data, the worst fit was obtained with the Site C Eastern coal data.

Coefficient "c" is of prime interest in this section because it relates nitric oxide emissions to grate heat release at constant excess air. The average coefficient c (i.e., .00041) indicates that an increase in grate heat release equivalent to 105 Btu/hr-ft^2 grate area will result in an increase in NO emissions of .041 lb/10^{6}Btu as NO_2 at constant excess air. Expressed in other units, an increase in load equivalent to 10% of capacity will result in an increase in NO emissions of approximately .025 lb/10^{6}Btu.

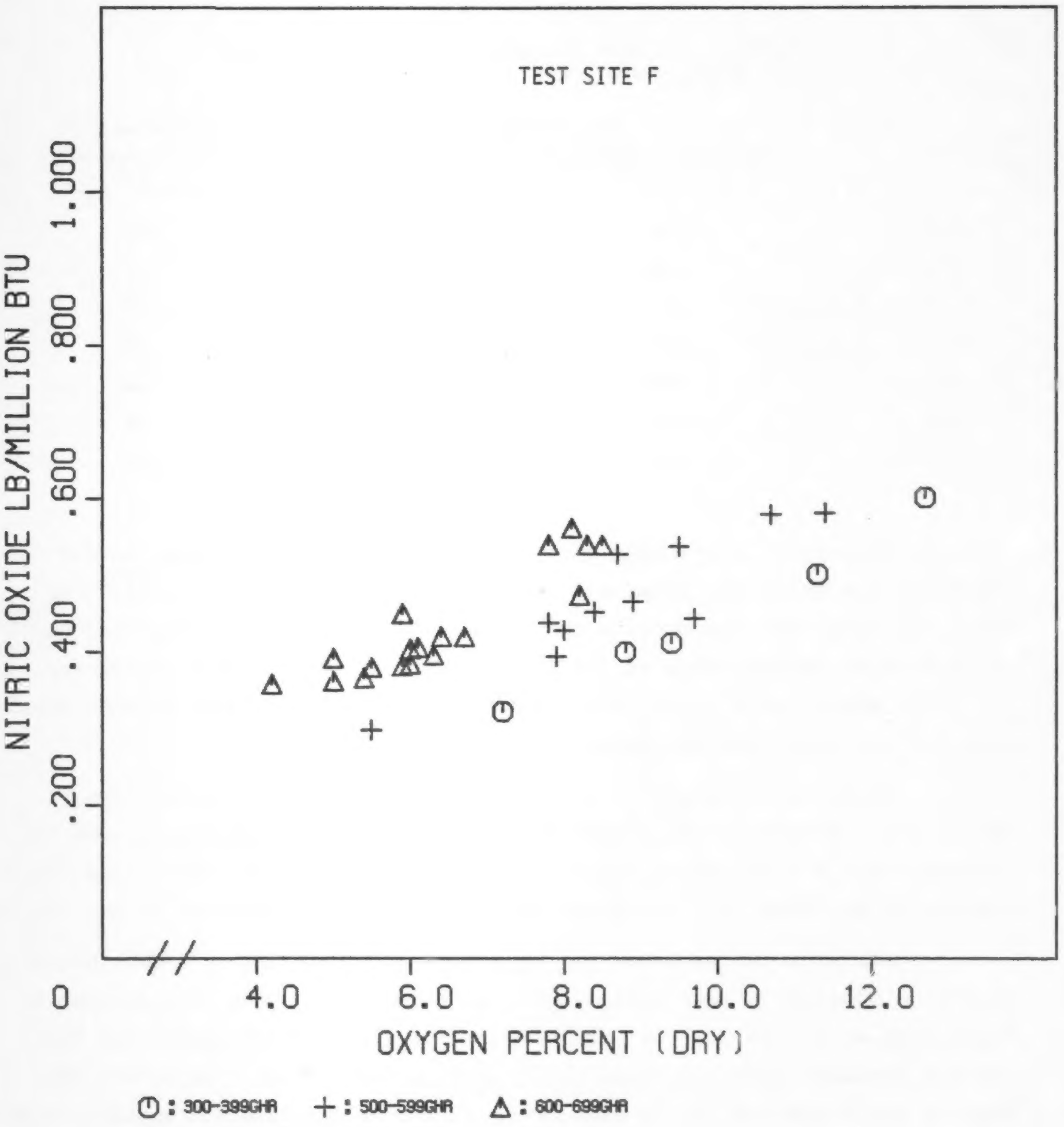

FIG. 3-32
NITRIC OXIDE VS. OXYGEN

TABLE 3-14

COEFFICIENTS FROM MULTIPLE REGRESSION ANALYSIS ON NITRIC OXIDE DATA FROM SPREADER STOKERS

	Coefficients for NO = a+b(Ex Air)+c(Grate Heat Release)			Coefficient of Determination
	a	b	c	R^2
Site A	.126	.00674	.00041	.66
Site B	.128	.00243	.00022	.68
Site C (Eastern)	.017	.00287	.00054	.40
Site C (Western)	.051	.00269	.00060	.59
Site E	.293	.00214	.00032	.58
Site F	-.034	.00360	.00046	.81
Site G	.151	.00334	.00029	.46

This model is a simple one. The true relationship between nitric oxide and the variables excess air and load are not necessarily linear. In fact, the model does not explain the 16% load data of Site G. Thus, the model is only valid between loads of 50% to 100% capacity, and between excess air limits of about 30% to 150%. Also, the model does not take into account other possible variables such as combustion air temperature.

Nitric oxide increased with load, or heat release rate, at constant excess air. However, under normal operation excess air decreases as load increases. The two influences cancel each other out such that nitric oxide concentration was relatively invariant with load on the six spreader stoker boilers.

Nitric oxide concentration might also be a function of stoker boiler design in addition to heat release rate and excess air. This is indicated in Table 3-15 by the average NOx emissions at full load and 50% excess air for the six spreader stokers. These averages range from .4 to .7 lb/10^6Btu NOx. Some of the variations can be explained. Test Site A's high NOx appears to be due to its high combustion air temperature. This relationship between high combustion air temperature and NOx has been noted by other researchers. At Sites E, F, C, and B, low NOx seems to correlate with low furnace liberation. Test Site C is unusual in that its NOx was low despite its high combustion air temperature.

TABLE 3-15

NITRIC OXIDE VS DESIGN VARIABLES

	Nitric Oxide @ Full Load & 50% Excess Air $lb/10^6Btu$	Combustion Air Temperature °F	Furnace Liberation $10^3Btu/hr\text{-}ft^3$	Grate Heat Release $10^3Btu/hr\text{-}ft^2$
Site A	.70	270	21.5	696
Site E	.55	92	22.6	674
Site G	.53	75	24.0	712
Site F	.47	80	23.5	688
Site C	.45	300	20.6	483
Site B	.40	60	20.4	713

3.3.6 Carbon Monoxide vs Heat Release Rate

Carbon monoxide increased whenever excess air was too low at high heat release rates, or too high at low heat release rates. Because of the differing operating conditions among the six spreader stokers, it was not possible to typify carbon monoxide emissions for spreader stokers. Each unit behaved differently.

At Site A, combustion conditions became unstable at full load when excess air dropped below 30%. This was indicated by highly variable and excessive carbon monoxide emissions. Sites C and F showed this same tendency but to a lesser extent.

At Site B, carbon monoxide emissions were low at full load but increased sharply at low loads. The tendency for carbon monoxide to increase at low loads was also evident to a lesser extent at Site F. Test Site E showed neither of these trends because tests were conducted over too narrow a range of operation.

Figure 3-33 shows the carbon monoxide trends with grate heat release for five spreader stokers. Carbon monoxide was not measured at Site G because the CO monitor was out-of-service.

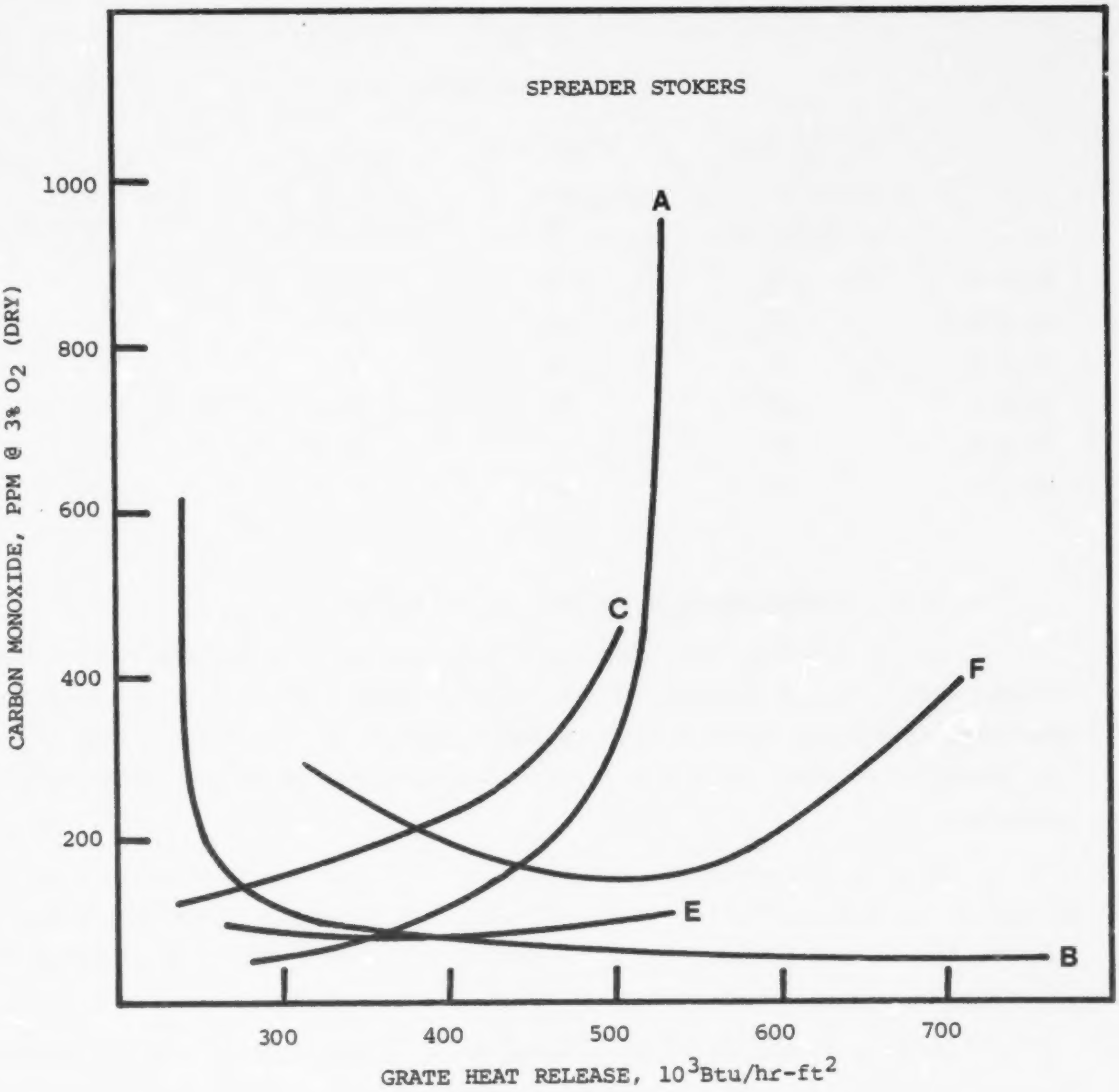

Figure 3-33. Carbon Monoxide Trends with Grate Heat Release for Five Spreader Stokers.

3.3.7 Unburned Hydrocarbons vs Heat Release Rate

Unburned hydrocarbons were measured only at Sites F and G. At these two sites, opposite trends were observed. At Site F, hydrocarbons decreased as full load was approached. At Site G, hydrocarbons increased. The hydrocarbon data are presented in Figure 3-34.

Unburned hydrocarbons did not correlate well with carbon monoxide at these two sites. That is to say, hydrocarbon emissions did not necessarily increase as carbon monoxide emissions increased.

3.3.8 Boiler Efficiency vs Heat Release Rate

The boiler efficiency data for all six spreader stokers are plotted against grate heat release in Figure 3-35. Boiler efficiency appears to be relatively constant at all heat release rates in this figure.

Examined separately, Sites B, C, and G had decreasing efficiencies as the heat release rate dropped. These decreases were related to the rapidly increasing excess air requirement, and the resultant increase in dry gas heat loss. It was also observed that boiler efficiencies dropped as full load was approached at Sites E, F, and G due to increasing combustible losses. Therefore, peak efficiencies were sometimes obtained in the vicinity of 80% of design steaming capacity.

It is necessary to sort out the effects of coal properties and abnormal operating conditions to obtain these efficiency trends. They are not immediately evident from the data plots. Nor are they true for all six units tested. The most unpredictable heat loss was the heat loss due to combustibles in the ash. Were it not for this, boiler efficiencies could be predicted with a great deal more accuracy.

3.4 RESPONSE TO EXCESS AIR

This section discusses the influence excess air had on the emissions and efficiency of spreader stokers. Excess air is primarily a function of load, decreasing as load increased under normal operating conditions. But, excess air also varies at constant load and this is the relationship that is of interest here.

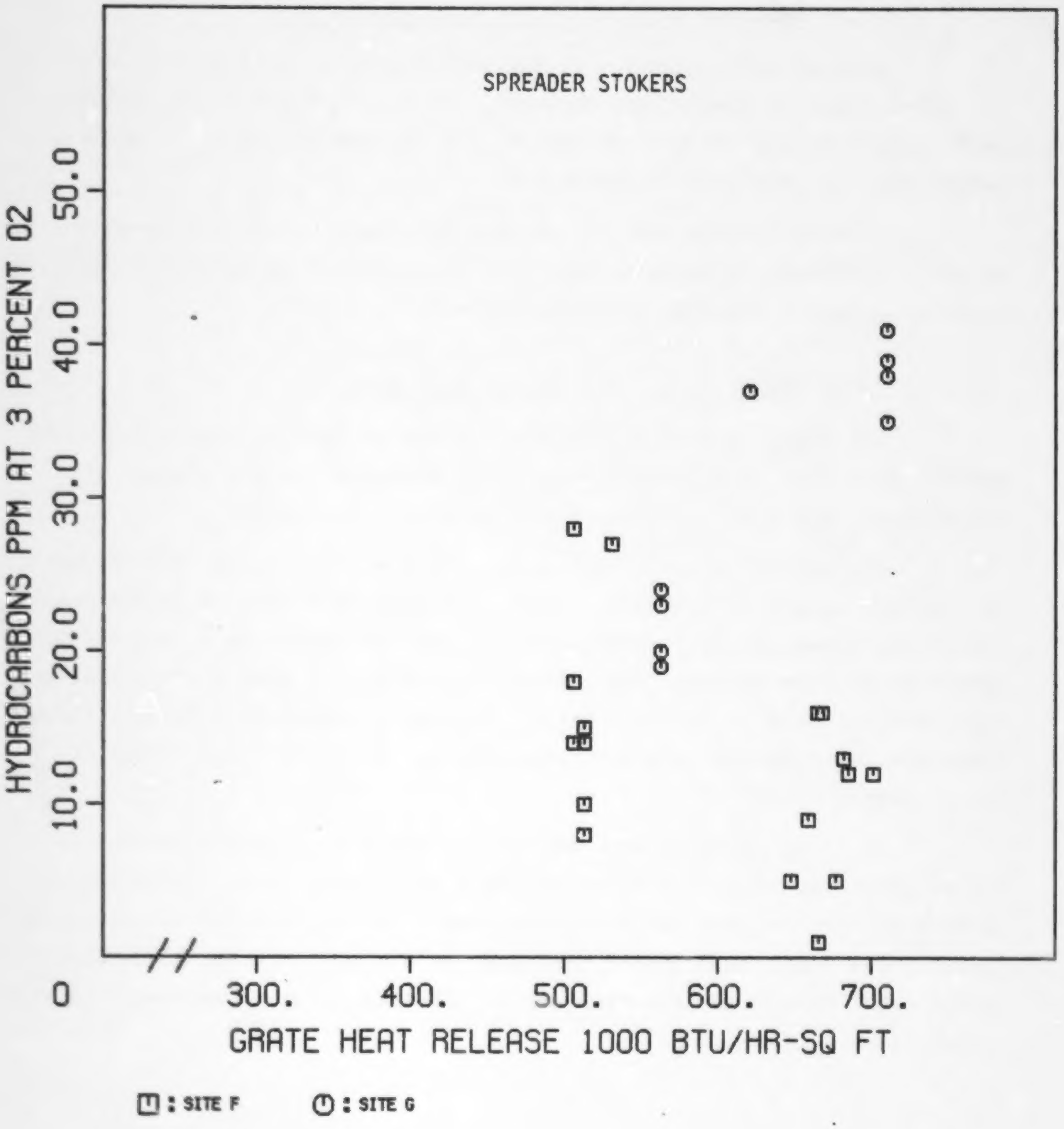

FIG. 3-34
HYDROCARBONS VS. GRATE HEAT RELEASE

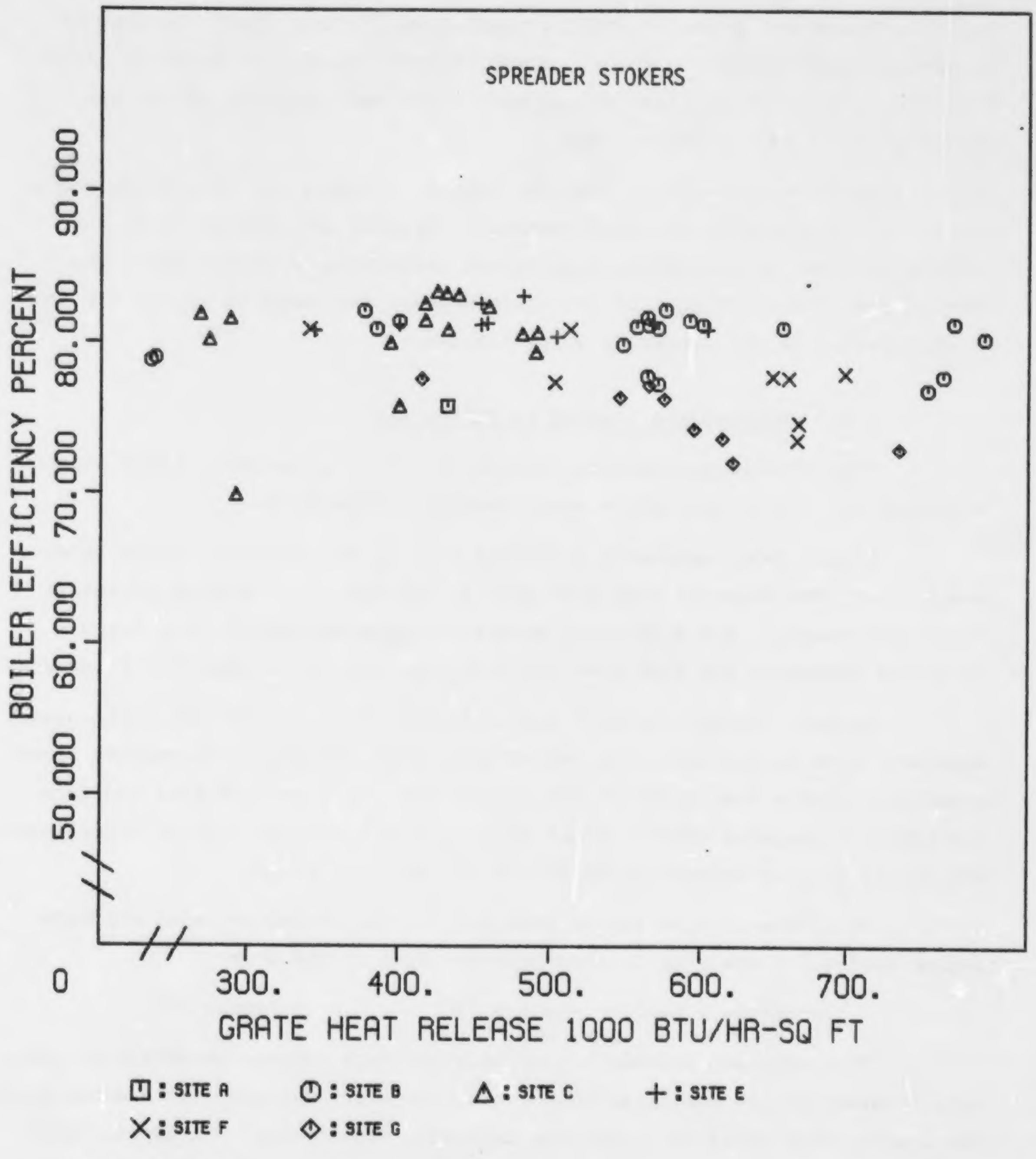

FIG. 3-35
BOILER EFFICIENCY VS. GRATE HEAT RELEASE

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The normal procedure during testing was to first test the unit at an as-found, or normal condition. These as-found conditions were, of course, dependent upon which operator was on duty since each operator set up his boiler in a slightly different way.

The next step was to test the unit at a higher and at a lower excess air level while keeping the load constant. Keeping the load constant was often a problem, as was making significant variations in excess air. The results are often difficult to interpret because the range of excess air data at any given load was generally quite limited.

3.4.1 Particulate Loading vs Excess Air

Uncontrolled particulate loading was found to be only weakly related to excess air, if at all, while other factors predominated.

Figure 3-36 represents a typical plot of particulate loading versus excess air. The data are from Test Site B, and the three symbols represent three load ranges: low load being 40-60% of capacity, medium load being 60-80% of capacity, and high load being all tests greater than 80% of capacity.

In this figure, the high load data indicate no trend for particulate loading versus excess air. The medium load data indicate an increasing trend based on a single test point at 90% excess air. The low load data indicate a slightly decreasing trend. Other sites showed a similar lack of orderliness, and it was usually impossible to determine any trend at all.

An alternate approach to this problem was attempted using multiple linear regression analysis to correlate the data to the form:

$$\text{Particulate Loading} = a + b\ (\%\ \text{Load}) + c\ (\%\ \text{Excess Air})$$

This approach assumes linear relationships between uncontrolled particulate loading and the variables load and excess air. The approach did not yield any trends which could be called statistically significant. It is concluded that there were too many uncontrolled variables and too narrow an excess air range to establish a relationship with excess air. The data neither refute nor support the existence of such a relationship.

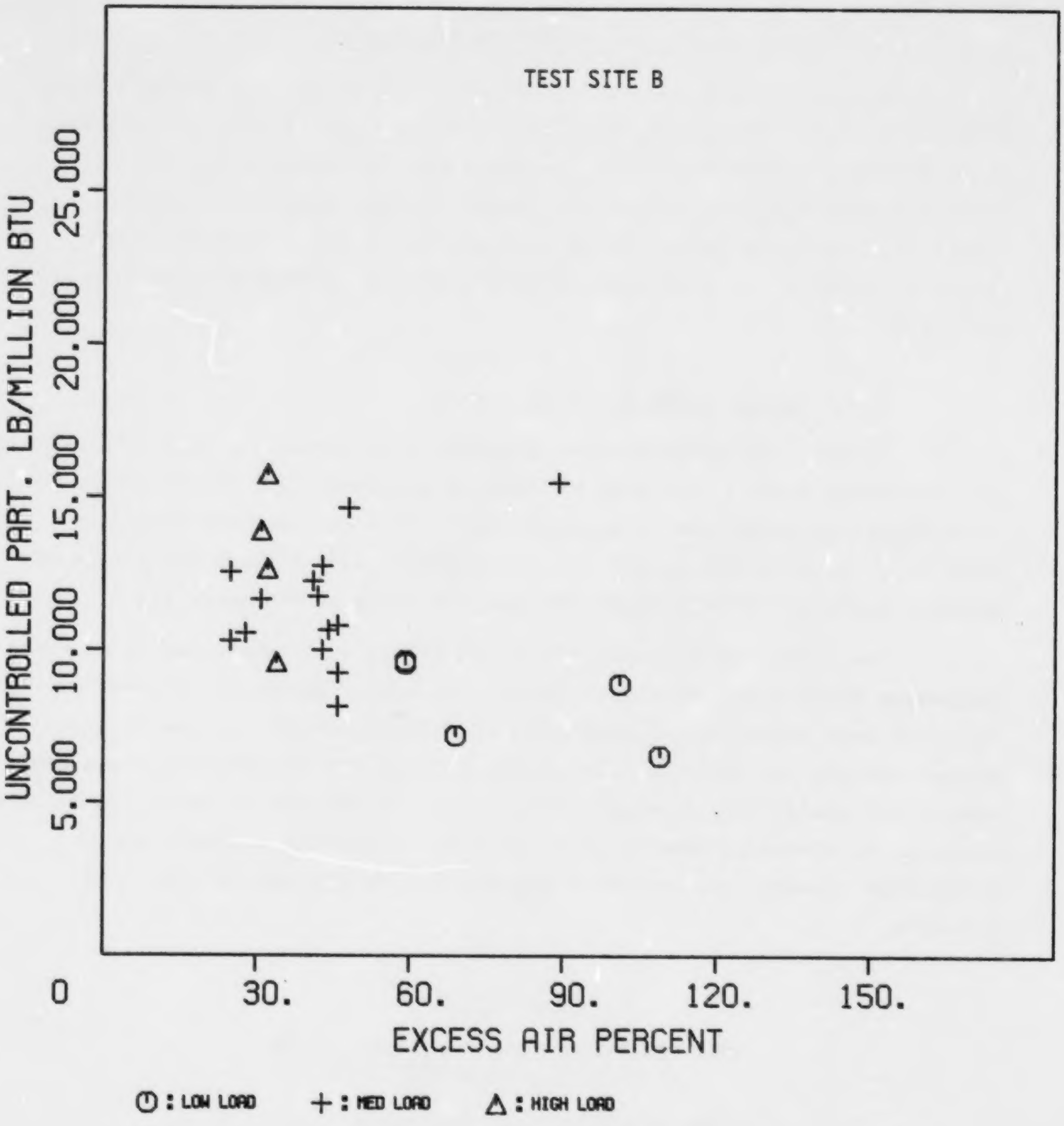

FIG. 3-36
UNCONTROLLED PART. VS. EXCESS AIR

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3.4.2 Combustibles in the Ash vs Excess Air

As with particulate loading, combustibles in the ash showed little or no correlation with excess air level. The Test Site B data are presented as an example. Figure 3-37 shows the percentage of combustibles in the uncontrolled flyash as a function of excess air for three load ranges. Figure 3-38 shows the percentage of combustibles in the bottom ash versus excess air. Again, if a correlation does exist, it is masked by uncontrolled variables.

3.4.3 Nitric Oxide vs Excess Air

Nitric oxide concentration increased with excess air in a well defined and consistent manner. The rate of increase averaged .0285 lb NOx/10^6Btu per 10% increase in excess air at constant load. This average rate applies to Sites B, C, D, E, F, and G, but does not apply to Site A which had a rate of increase equal to .0674 lb NOx/10^6Btu per 10% increase in excess air.

The nitric oxide-excess air relationships were determined by multiple regression analysis and by visual means. The visual method considered only the full load data while the multiple regression analysis took all the data into account and assumed that the relationship between NOx and excess air was the same at all loads. The agreement between the two methods was good. Table 3-16 presents the slopes as determined by multiple regression analysis, and Figure 3-39 presents the same data graphically for the case of full load operation.

TABLE 3-16

RELATIONSHIP BETWEEN NITRIC OXIDE AND
EXCESS AIR AT CONSTANT LOAD

	NOx(lb/10^6Btu) per 10% Excess Air
Site A	.0674
Site B	.0243
Site C (Eastern Coal)	.0287
Site C (Western Coal)	.0269
Site E	.0214
Site F	.0360
Site G	.0334

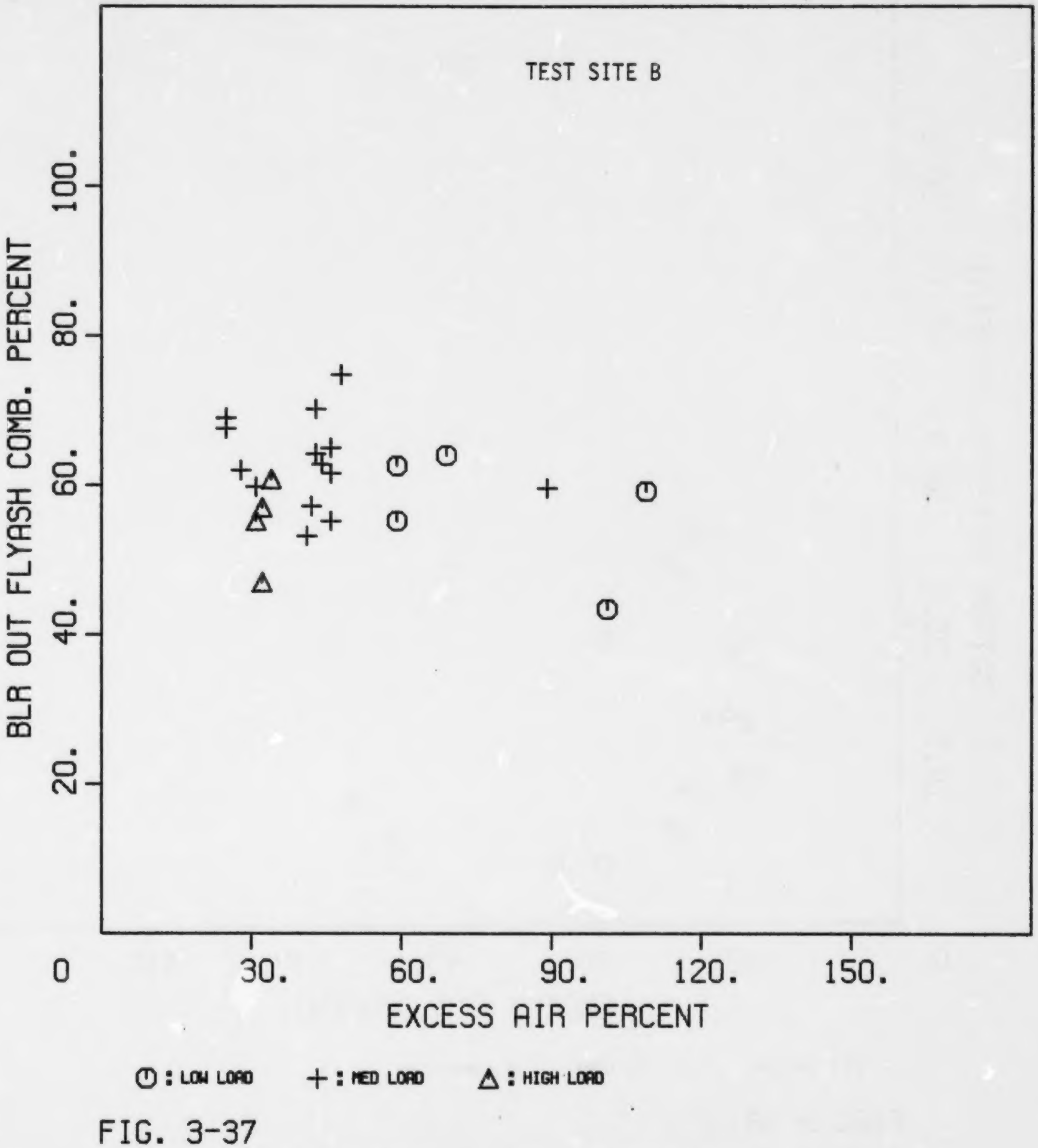

FIG. 3-37
BLR OUT FLYASH COMB. VS. EXCESS AIR

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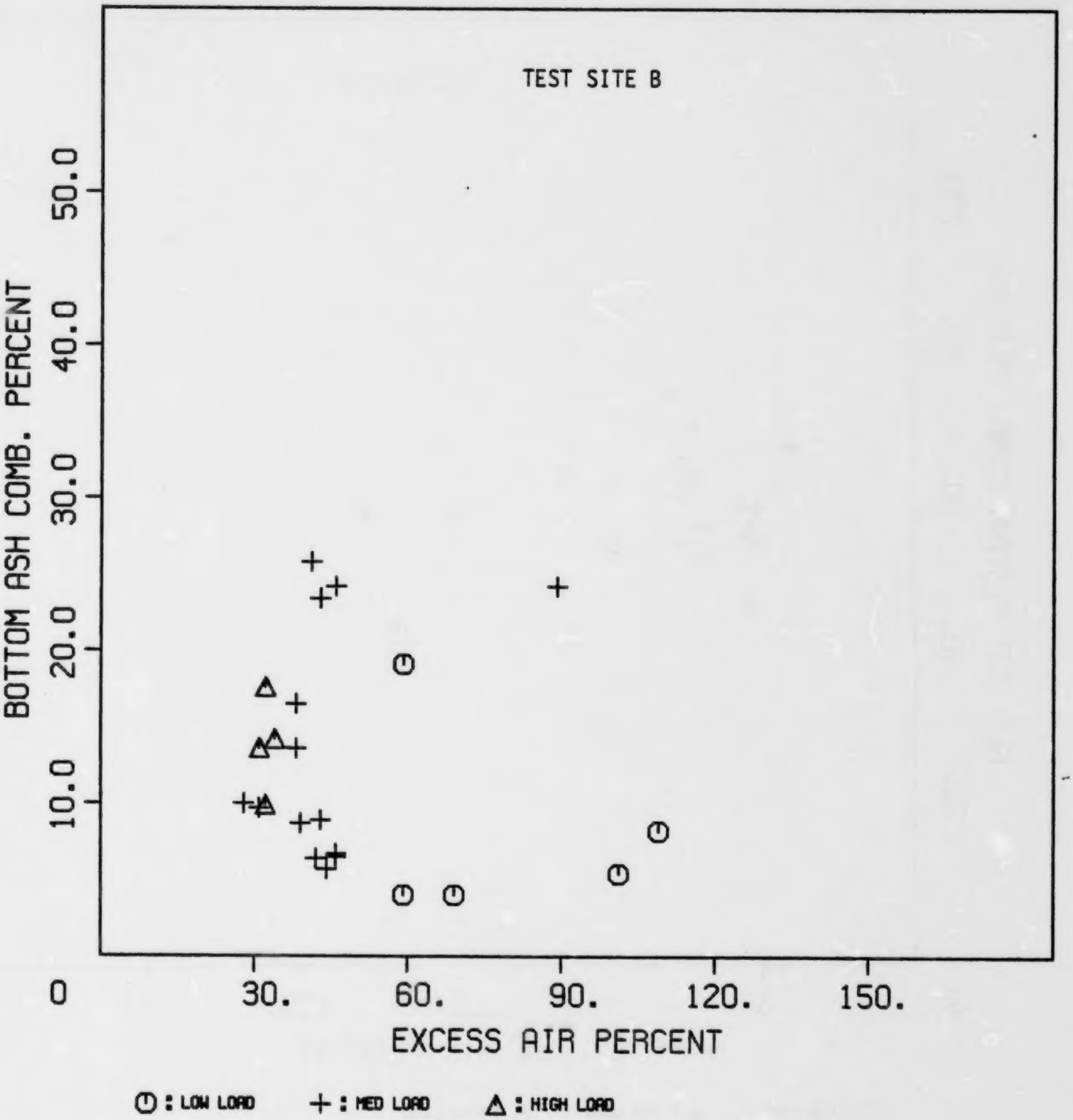

FIG. 3-38
BOTTOM ASH COMB. VS. EXCESS AIR

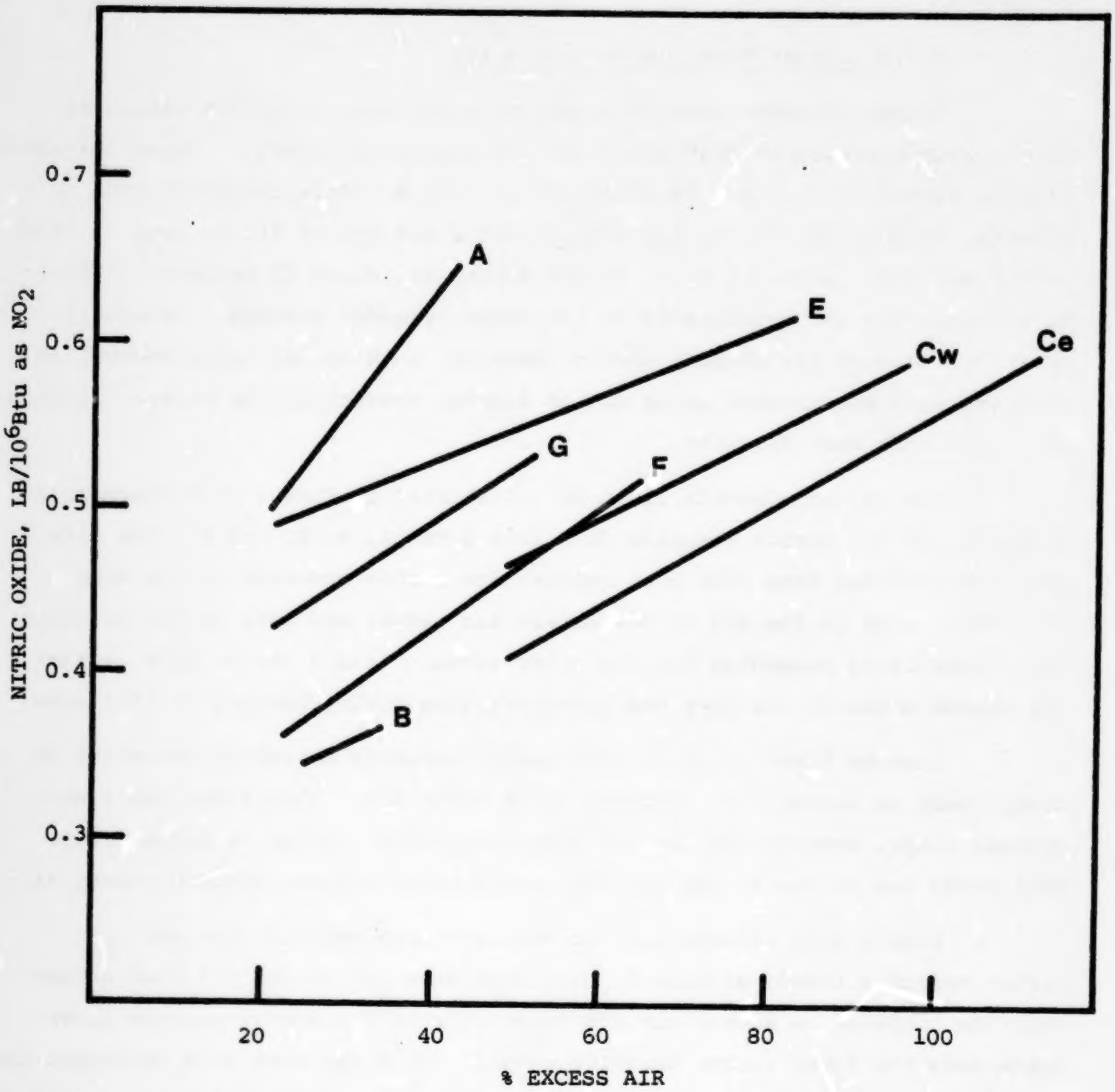

Figure 3-39. The Relationship Between Nitric Oxide and Excess Air Under Full Load Conditions on Six Spreader Stokers.

3.4.4 Carbon Monoxide vs Excess Air

Carbon monoxide emissions were very critical to boiler tuning at Site A when operated at high loads and low excess air levels. Below 30% excess air, CO ranged from 61 ppm to 2000+ ppm at Site A. This trend was true to a lesser extent when excess air dropped below 40% excess air at Site F. The carbon monoxide limit, or point at low excess air where CO becomes difficult to control, was not established on the other spreader stokers. Generally speaking, testing was stopped when clinkering, smoking, or other combustion problems were encountered so as not to disrupt operations, or strain relationships with the host facility.

The carbon monoxide limit is illustrated in Figure 3-40 which is a composite of all carbon monoxide data from Sites A, B, E, and F. The Site C data was excluded from this plot because its carbon monoxide levels were relatively high in the 60% to 90% excess air range, and this tended to cloud the trends being presented for the other sites. Site G has no data because the carbon monoxide analyzer was out-of-service during testing at that site.

Another trend noted is that carbon monoxide emissions increased at lower loads as excess air increased above about 50%. This trend has a more gradual slope, whereas the low air limit described earlier is quite steep. This trend may be due to the cooling and quenching effects of high excess air.

Figure 3-41 illustrates the relationships between load and the carbon monoxide trends at Site F. Not only does medium and low load carbon monoxide increase as excess air increases, but at 50% excess air the lower loads have the lower carbon monoxide levels. This may mean that increased carbon monoxide is being formed at high loads because the residence time in the flame zone is reduced at higher loads.

3.4.5 Unburned Hydrocarbons vs Excess Air

Unburned hydrocarbons, assumed to be primarily methane, were measured at Sites F and G. The data are plotted as a function of excess air in Figure 3-42.

The only observed trend with excess air occurred with the 80% load data at Test Site G. These levels, based on four readings, decreased as excess air increased. This trend is not illustrated.

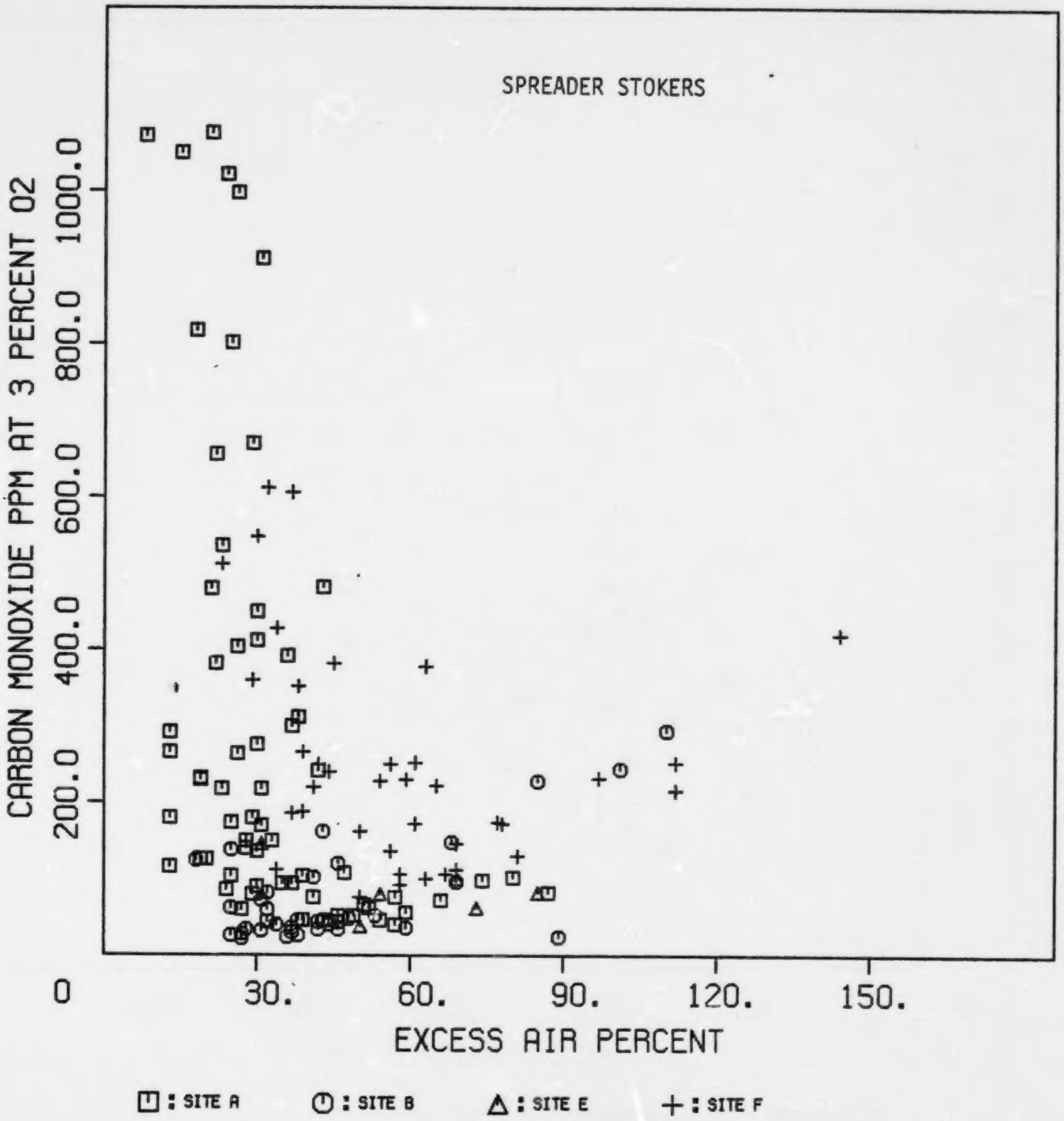

FIG. 3-40

CARBON MONOXIDE VS. EXCESS AIR

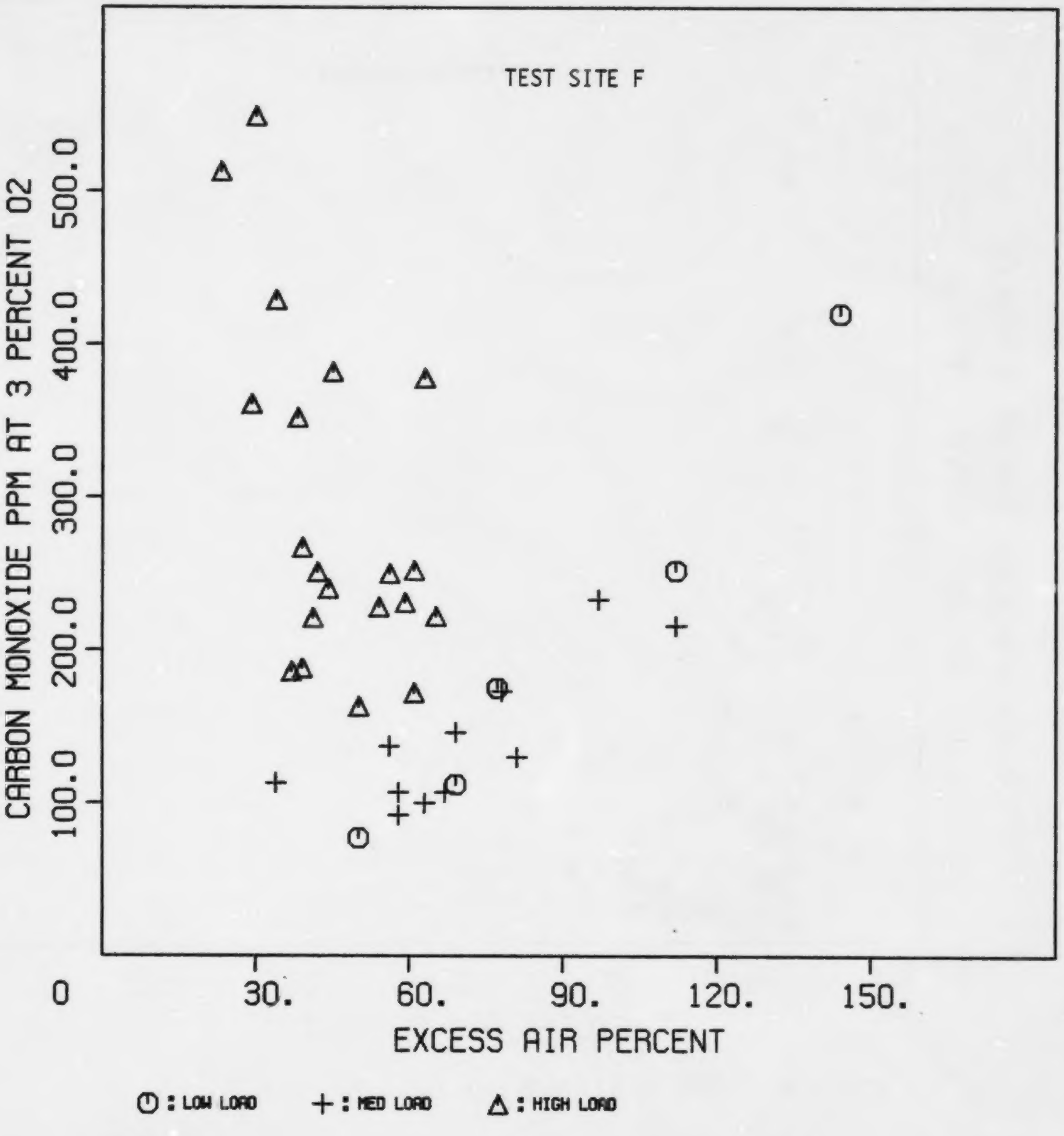

FIG. 3-41
CARBON MONOXIDE VS. EXCESS AIR

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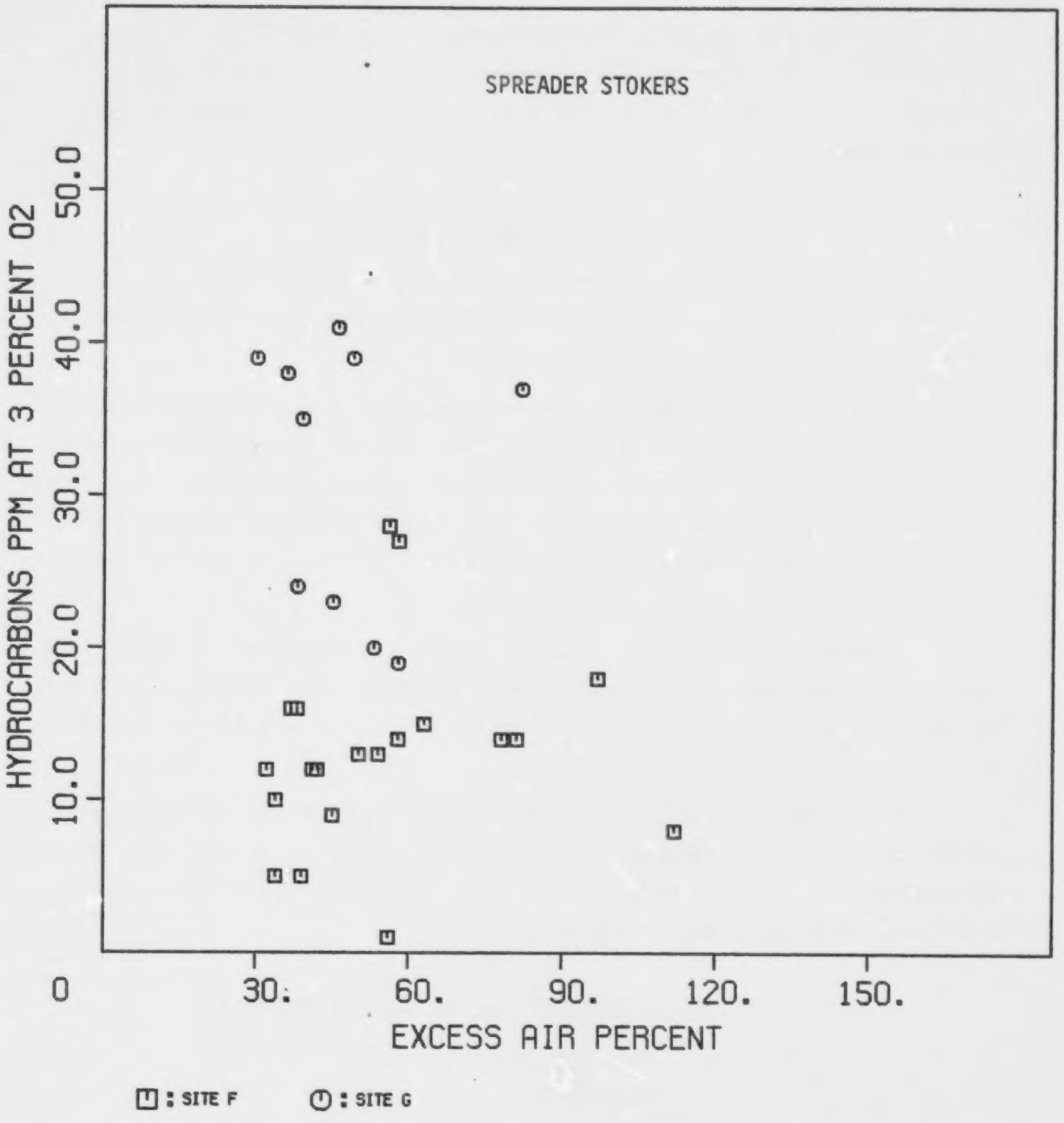

FIG. 3-42
HYDROCARBONS VS. EXCESS AIR

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It was also determined that hydrocarbon concentration did not correlate with carbon monoxide concentration at Site F. A similar correlation check could not be made at Site G because Site G lacked carbon monoxide data.

3.4.6 Boiler Efficiency vs Excess Air

Boiler efficiency decreased as excess air increased on all six spreader stokers. Dry gas heat losses dominated this trend, overshadowing any effects due to combustible heat losses.

The combustible and dry gas heat loss data for Test Site G are presented as an example. Figures 3-43 and 3-44 show the general lack of trend with excess air for the flyash and bottom ash combustible losses respectively. Figure 3-45 presents the dry gas heat loss data. Note that the dry gas heat loss is a function of boiler steaming capacity, or load, in addition to excess air.

The boiler efficiency data for Site G are presented in Figure 3-46. Again, it is apparent that steaming capacity was a major variable along with excess air. At constant excess air, boiler efficiency was higher at reduced loads.

The other spreader stokers behaved in a manner similar to that of the stoker at Site G, but exhibited a weaker relationship to excess air. Their relationships are listed below, with the exception of Site A, for which insufficient efficiency data existed.

EFFICIENCY GAIN PER 10% EXCESS AIR DECREASE

Site B	.53%
Site C	.55%
Site E	.33%
Site F	.67%
Site G	1.00%

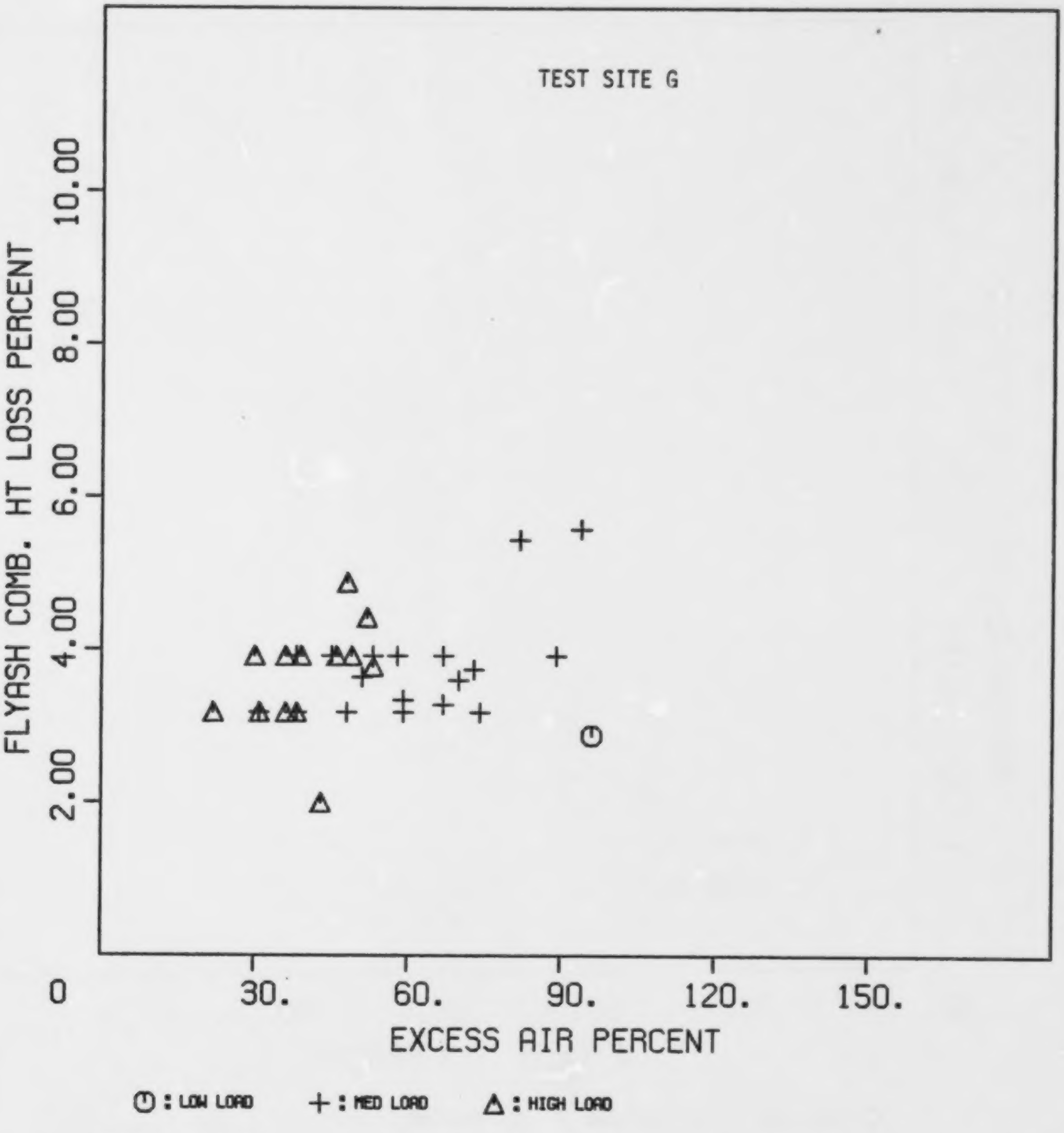

FIG. 3-43
FLYASH COMB. HT LOSS VS. EXCESS AIR

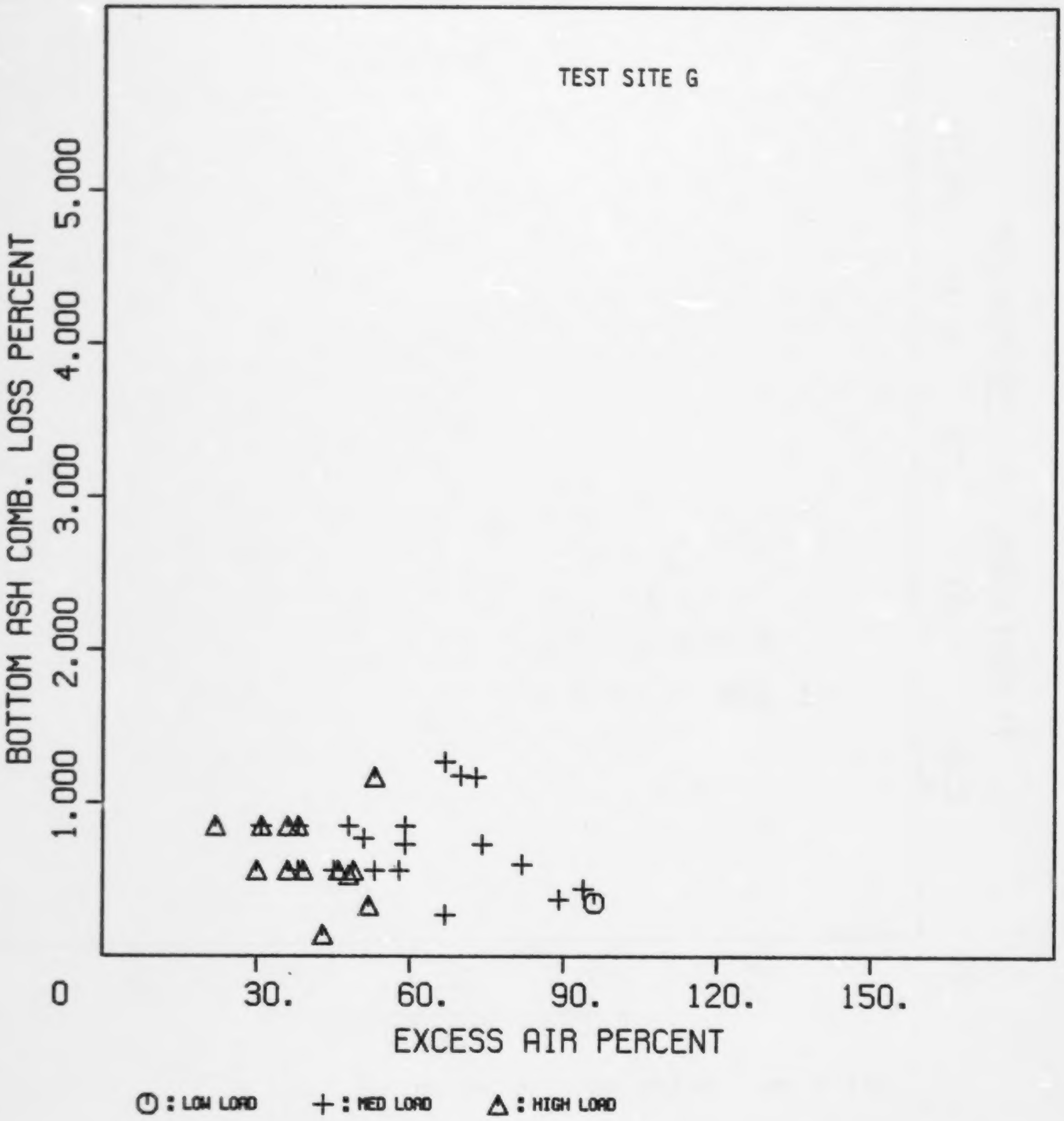

FIG. 3-44
BOTTOM ASH COMB. LOSS VS. EXCESS AIR

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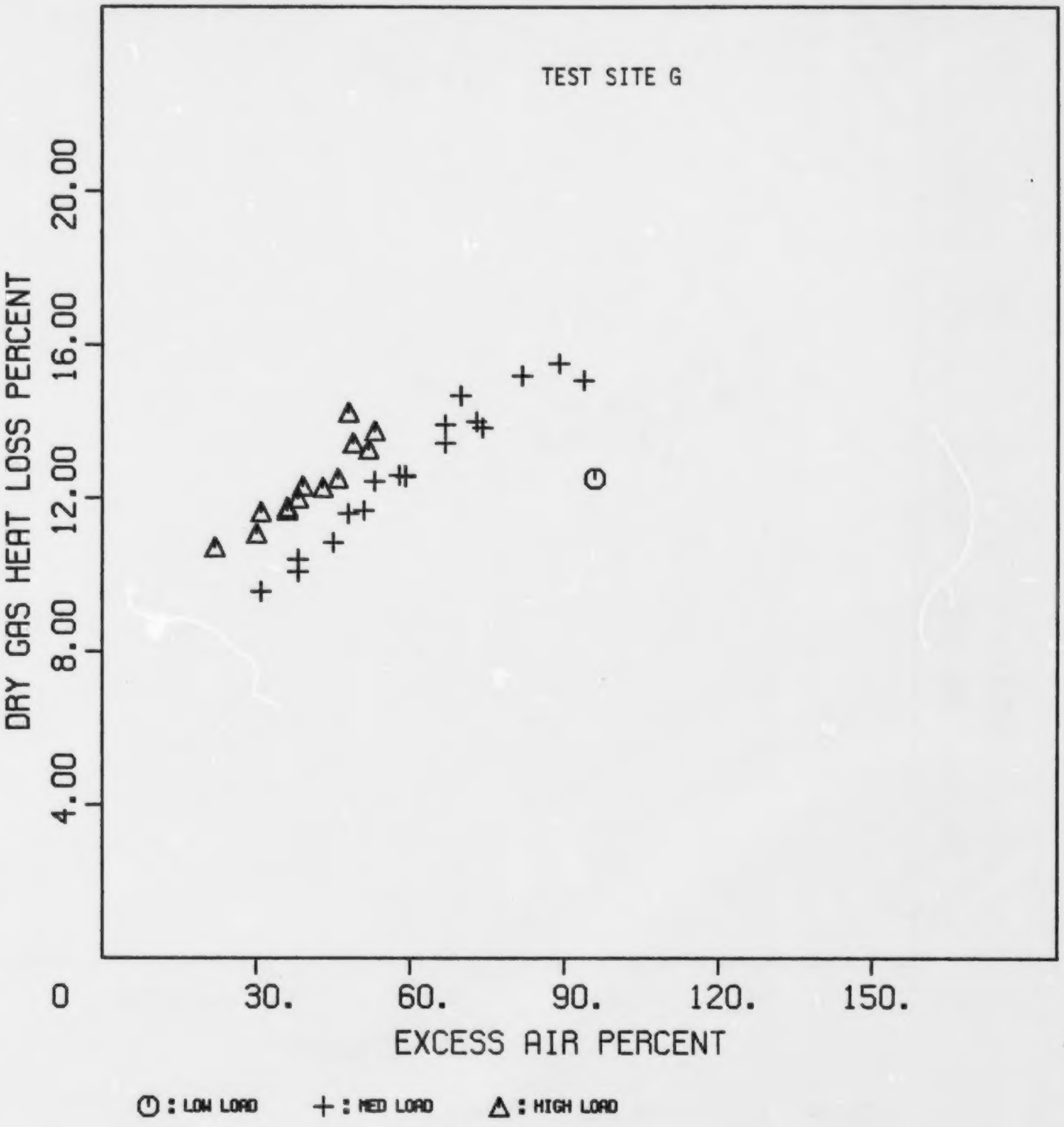

FIG. 3-45
DRY GAS HEAT LOSS VS. EXCESS AIR

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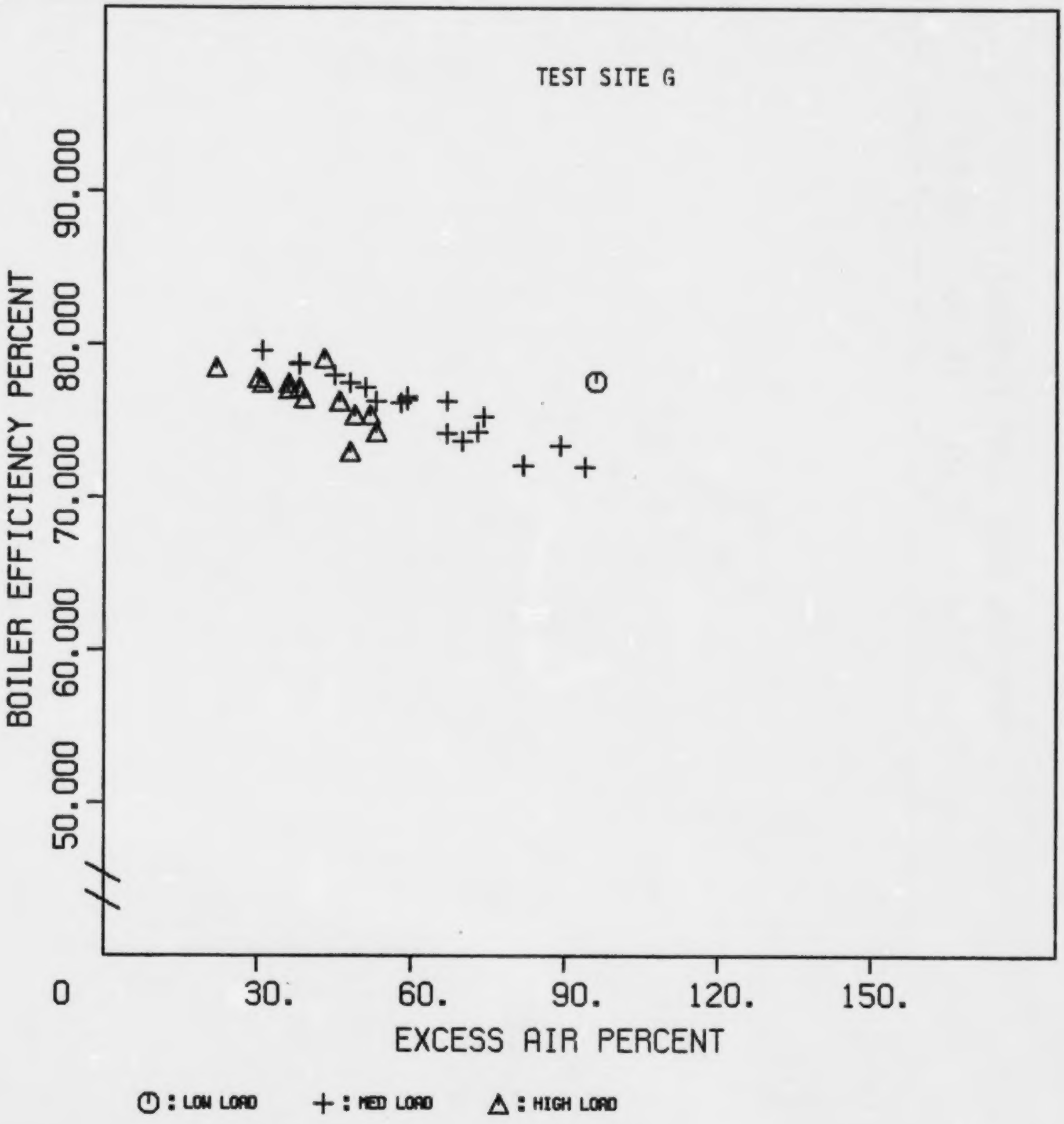


FIG. 3-46
BOILER EFFICIENCY VS. EXCESS AIR

4-15800-554

3.5 RESPONSE TO COAL ANALYSIS AND SIZING

Coals from several different mines were fired in each stoker, allowing for an evaluation of coal properties as a test variable. In most cases the coals were quite similar to each other, and produced quite similar emissions. In one case, however, an Eastern bituminous coal and a Western sub-bituminous coal were fired in the same boiler and did exhibit different emission characteristics.

Where coal properties were similar from one coal to another, it was often possible to correlate emissions with coal variations observed on a test-by-test basis. This was made possible by obtaining coal samples close enough to the stoker that they could be correlated directly with the test being conducted.

The coal properties are summarized in the six accompanying tables. Each table presents the average analysis for each of eighteen coal-stoker combinations. The tables include: coal identification and ASTM classification, proximate analysis, ultimate analysis, fusion temperature of the ash, mineral analysis of the ash, and coal size consistency. The data base includes the following number of samples for each analysis:

Proximate	- 141 samples	(Table 3-18)
Ultimate	- 52 samples	(Table 3-19)
Ash Fusion	- 33 samples	(Table 3-20)
Mineral	- 32 samples	(Table 3-21)
Size Consist	- 136 samples	(Table 3-22)

3.5.1 Particulate Loading vs. Coal Properties

Two properties were examined for their relationship to particulate loading. These are coal ash on a mass percent basis, and coal fines. Each will be presented separately.

Coal Ash. An examination of Table 3-18, Proximate Analysis, indicates that coal ash was a significant variable only at Sites A and G. At least, this is the case when comparing the averages.

The Site A data, shown in Figure 3-47, shows very little difference in particulate loading between the two coals. The Site G data, on the other hand, does indicate a considerable difference in loading at full load, yet indicates no difference at low load. (Figure 3-48)

TABLE 3-17

COAL IDENTIFICATION AND CLASSIFICATION* SPREADER STOKERS

	Coal	Identification	ASTM Classification	Fixed Carbon (Dry, Mineral Matter-Free Basis)	Volatile Matter (Dry, Mineral Matter-Free Basis)	Calorific Value (Moist, Mineral Matter-Free Basis)
Site A	1	Stansbury	Subbituminous A	57	43	11,300
	2	Kemmerer	Subbituminous A	56	44	10,720
	3	Consolidation	High Volatile C Bituminous	57	43	11,620
Site B	1	Kentucky Cumberland	High Volatile A Bituminous	62	38	14,450
	2	Hatfield	High Volatile A Bituminous	62	38	14,550
	3	Southeast	High Volatile A Bituminous	62	38	14,650
	4	Reload	High Volatile A Bituminous	62	38	14,450
Site C (E)	1	Eastern Low Fusion	High Volatile A Bituminous	59	41	14,030
(W)	2	Western	Subbituminous C	56	44	9,410
(E)	3	Eastern High Fusion	High Volatile B Bituminous	63	37	13,190
Site E	1	Kentucky	High Volatile A Bituminous	60	40	14,090
	2	Crushed Kentucky	High Volatile A Bituminous	61	39	14,250
	3	Eastern Kentucky	High Volatile B Bituminous	60	40	13,980
Site F	1	Pennsylvania A	Medium Volatile Bituminous	70	30	15,000
	2	Pennsylvania B	Medium Volatile Bituminous	71	29	15,060
Site G	1	White Ash	High Volatile A Bituminous	60	40	14,120
	2	Spurlock	High Volatile A Bituminous	58	42	14,600
	3	Pevler	High Volatile B Bituminous	59	41	13,960

* Coal was Classified by rank using the Parr Formulas and ASTM D 388.

TABLE 3-18

PROXIMATE COAL ANALYSIS
SPREADER STOKERS

	Coal	Weight Percent as-Fired Moisture	Ash	Volatile	Fixed Carbon	Btu/lb	% Sulfur
Site A	1	14.38	6.07	34.71	44.84	10546	.93
	2	18.80	3.47	34.70	43.05	10310	.63
	3	12.82	7.89	34.15	45.14	10628	.40
Site B	1	4.27	7.72	34.24	53.77	13220	.90
	2	3.93	8.79	33.65	53.63	13137	.93
	3	2.90	9.02	34.19	53.89	13201	.78
	4	4.38	6.40	34.71	54.51	13432	.77
Site C	1	5.31	11.17	35.02	48.49	12262	2.89
	2	25.63	9.02	28.94	36.35	8493	.70
	3	9.09	9.24	30.94	50.72	11854	.88
Site E	1	6.12	8.52	35.06	50.29	12773	.86
	2	5.69	9.08	33.50	51.73	12831	.71
	3	6.30	8.21	34.47	51.01	12722	.77
Site F	1	4.06	10.55	26.27	59.11	13242	1.47
	2	3.85	9.39	25.68	61.09	13502	1.00
Site G	1	4.56	8.04	35.19	52.17	12869	.78
	2	3.01	4.42	38.97	53.59	13860	1.31
	3	4.59	7.32	36.29	51.79	12832	.75

TABLE 3-19

ULTIMATE COAL ANALYSIS
SPREADER STOKERS

		Weight Percentage as-Fired							
	Coal	Moisture	Carbon	Hydrogen	Nitrogen	Chlorine	Sulfur	Ash	Oxygen
Site A	1	13.96	60.47	4.16	0.99	0.01	0.99	6.85	12.59
	2	18.81	59.68	4.08	0.85	0.01	0.66	3.45	12.48
	3	13.06	62.19	4.11	0.82	0.01	0.35	7.81	11.65
Site B	1	3.88	72.74	4.92	1.05	0.10	0.96	9.22	7.13
	2	3.31	72.88	4.88	1.43	0.10	0.93	9.87	6.62
	3	2.95	73.34	4.92	1.26	0.13	0.79	10.01	6.61
	4	5.97	73.45	4.94	1.45	0.12	0.73	6.72	6.65
Site C	1	3.45	71.05	4.79	1.18	0.07	2.76	10.49	6.22
	2	25.04	50.92	3.28	0.94	0.01	0.60	8.76	10.45
	3	13.27	64.30	4.02	1.41	0.07	0.75	7.93	8.25
Site E	1	6.13	71.69	4.73	1.30	0.13	0.86	8.52	6.67
	2	5.69	71.95	4.72	1.36	0.14	0.71	9.08	6.36
	3	6.31	71.31	4.70	1.13	0.08	0.78	8.21	7.50
Site F	1	3.28	75.14	4.61	1.23	0.15	1.42	10.52	3.68
	2	3.69	70.36	4.69	1.12	0.17	1.00	8.96	4.03
Site G	1	4.18	72.26	4.72	0.98	0.10	0.75	8.92	8.09
	2	3.32	74.59	5.11	1.12	0.18	1.31	6.56	7.81
	3	4.63	72.67	4.88	1.00	0.05	0.67	7.10	9.01

TABLE 3-20

FUSION TEMPERATURE OF THE ASH
REDUCING ATMOSPHERE - SPREADER STOKERS

	Coal	Initial Deformation	Softening H=W	Softening H=½W	Fluid
Site A	1	2000 °F	2190 °F	2240 °F	2640 °F
	2	2200	2300	2393	2488
	3	2170	2265	2355	2420
Site B	1	2490	2643	2673	2700+
	2	2550	2700+	2700+	2700+
	3	2607	2700+	2700+	2700+
	4	2700+	2700+	2700+	2700+
Site C	1	2023	2155	2288	2410
	2	2180	2250	2317	2375
	3	2145	2235	2330	2420
Site E	1	2700+	2700+	2700+	2700+
	2	2700+	2700+	2700+	2700+
	3	2700+	2700+	2700+	2700+
Site F	1	2560	2650	2675	2700+
	2	2700+	2700+	2700+	2700+
Site G	1	2700+	2700+	2700+	2700+
	2	2420	2650	2680	2700+
	3	2700+	2700+	2700+	2700+

TABLE 3-21

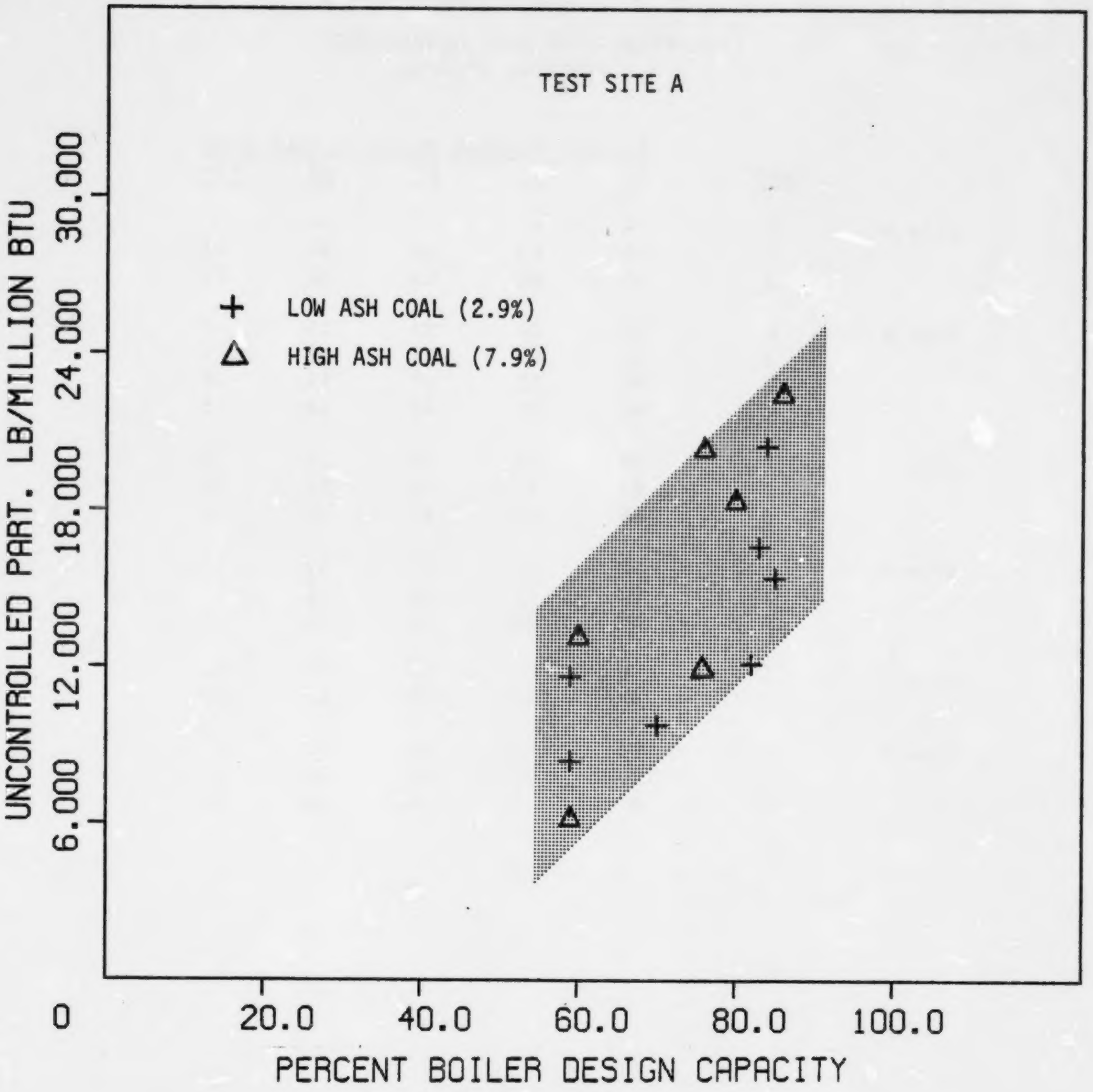
MINERAL ANALYSIS OF THE ASH
SPREADER STOKERS

	Coal	Silica SiO_2	Alumina Al_2O_3	Titania TiO_2	Ferric Oxide FeO_3	Lime CaO	Magnesia MgO	Potassium Oxide K_2O	Sodium Oxide Na_2O	Sulfur Trioxide SO_3	Phosphorus Pentoxide P_2O_5	Undetermined
Site A	1	59.32	12.90	0.55	11.10	5.90	2.16	1.06	0.32	5.71	0.19	0.77
	2	51.88	18.49	0.75	5.02	8.12	2.76	0.90	0.32	10.77	0.18	0.81
	3	46.02	18.65	0.70	6.96	14.80	1.62	0.65	1.02	8.23	0.78	0.57
Site B	1	53.99	28.44	1.21	7.65	2.24	1.27	2.25	0.56	1.39	0.28	0.72
	2	54.82	28.58	1.49	7.30	1.63	1.10	2.18	0.60	1.02	0.39	0.92
	3	54.14	29.75	1.47	6.92	1.95	0.84	1.44	0.50	1.15	0.45	1.39
	4	53.77	30.36	1.38	6.79	1.94	0.86	1.70	0.45	1.43	0.30	1.06
Site C	1	43.69	21.36	1.07	23.91	2.05	2.05	1.75	0.56	2.91	0.23	0.11
	2	42.61	17.85	0.92	5.67	13.97	3.83	0.62	0.59	12.94	0.19	0.82
	3	49.23	23.21	1.14	10.05	5.50	2.12	1.75	0.50	6.24	0.18	0.08
Site E	1	52.67	31.68	3.71	6.22	1.64	0.77	1.88	0.26	0.81	0.18	0.03
	2	52.03	33.59	1.66	5.34	1.95	1.08	2.56	0.32	0.76	0.49	0.06
	3	49.80	36.27	1.63	5.19	2.07	0.88	2.07	0.25	1.15	0.43	0.06
Site F	1	45.06	32.43	1.35	13.23	2.23	0.67	1.90	0.29	1.86	0.62	0.23
	2	47.85	33.42	1.42	9.95	1.39	0.66	1.95	0.41	1.41	0.38	0.96
Site G	1	52.89	31.29	1.40	6.99	1.61	1.03	2.46	0.48	0.79	0.17	0.22
	2	43.26	30.37	1.21	13.50	3.43	1.32	2.05	0.61	3.61	0.19	0.45
	3	51.00	37.18	1.92	4.14	1.26	0.81	1.57	0.29	0.61	0.16	0.27

TABLE 3-22

AS-FIRED COAL SIZE CONSISTENCY
SPREADER STOKERS

		Percent Passing Stated Screen Size				
	Coal	1"	½"	¼"	#8	#16
Site A	1	--	--	--	--	--
	2	98	83	58	31	19
	3	97	84	62	36	23
Site B	1	95	56	27	13	9
	2	95	65	34	16	9
	3	96	55	27	13	8
	4	94	48	24	13	8
Site C	1	90	68	46	22	11
	2	93	71	48	27	16
	3	85	63	44	26	16
Site E	1	92	64	37	19	11
	2	93	57	31	15	10
	3	88	62	41	22	14
Site F	1	96	62	27	16	13
	2	97	59	28	17	12
Site G	1	98	73	41	20	12
	2	100	50	22	13	10
	3	97	73	36	16	10



+ : 2.9 ASH Δ : 7.9 ASH

FIG. 3-47
UNCONTROLLED PART. VS. PERCENT DESIGN CAPACITY

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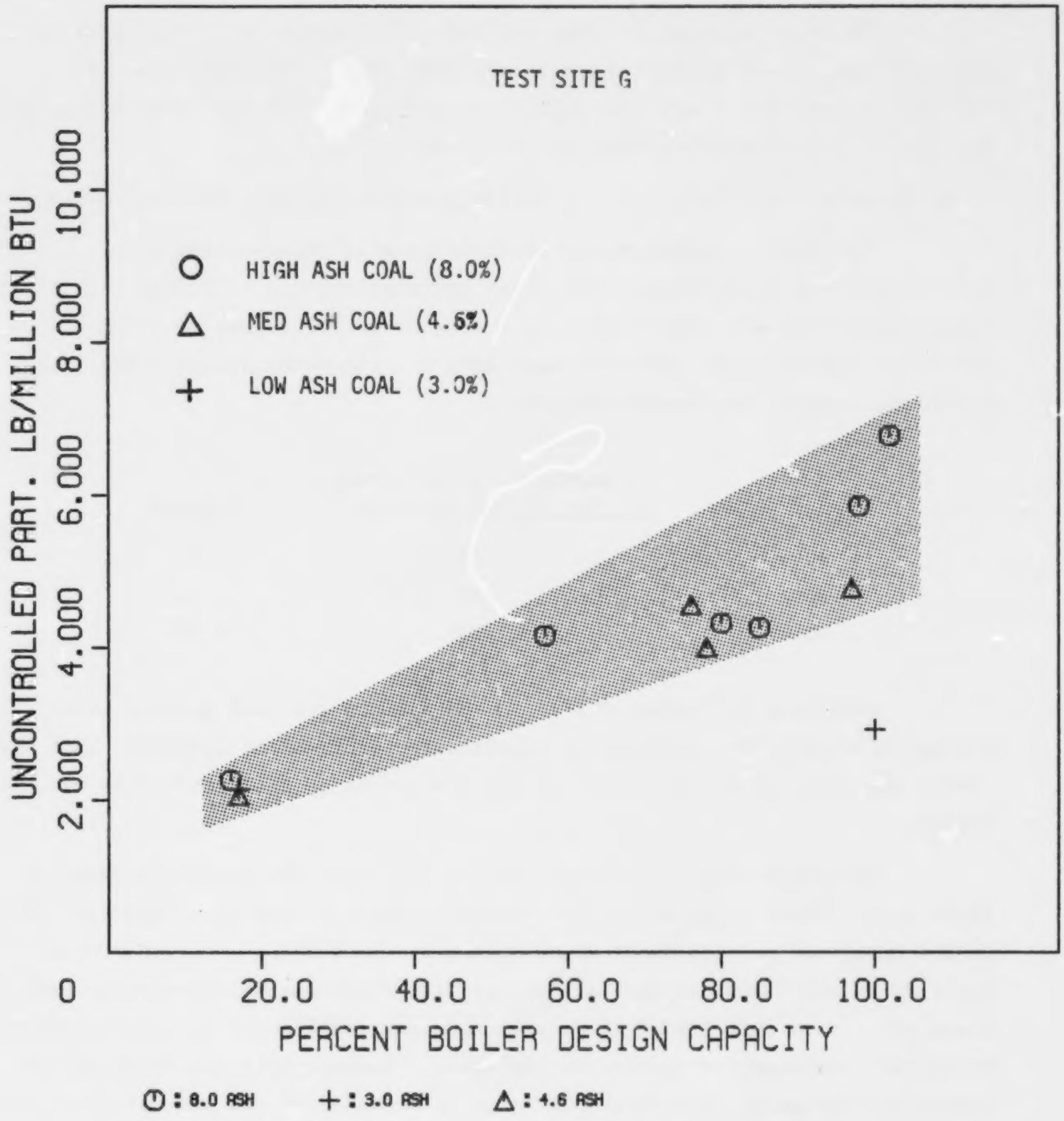

FIG. 3-48
UNCONTROLLED PART. VS. PERCENT DESIGN CAPACITY

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The above examination does not take into account the variations in coal ash experienced between tests on the same coal. This variation was examined by the use of multiple regression analysis. The data from each site were fit to a mathematical model of the form:

$$\text{Particulate, lb}/10^6\text{Btu} = a+b(\%\ \text{Load})+c(\%\ \text{Excess Air})+d(\%\ \text{Ash})+e(\%\ \text{Fines})$$

The results indicated correlations at only three of six sites. Again, Site A showed no correlation. The three correlations are indicated here along with their "T-value". The T-value is a measure of the degree to which the individual variable, in this case coal ash, fit the mathematical model. The higher the number, the better the fit.

	Δ Particulate, lb/10^6Btu per 1% Ash Increase	T-Value
Site B	.24	1.97
Site F	.34	4.13
Site G	.38	2.31

This data indicates that a 1% increase in coal ash results in an average 0.32 lb/10^6Btu increase in uncontrolled particulate loading. This trend covers the range of 4.3 to 16.8% ash and should not be extrapolated beyond these limits.

The percentage of coal ash carried over with the flyash is shown in Table 3-23. Sites A, B, and C show unusually high ash carryover numbers. This is the result of reentrainment of a large portion of the reinjected flyash. Sites E, F, and G did not reinject flyash from their mechanical dust collectors. These sites show that 27% of the coal ash is carried over in spreader stokers, while the remaining 73% remains on the grate. Because this ash contains some combustible material, the as-found flyash (inorganic ash and combustibles) represents 73% by weight of the coal ash, while 91% by weight remains on the grate.

TABLE 3-23

ASH BALANCE
SPREADER STOKERS

	Coal	Inorganic Ash as % of Coal Ash		As-Found Ash*as % of Coal Ash	
		% Carryover	% Grate	% Carryover	% Grate
Site A	2	201		343	
	3	89		178	
Site B	1	75		188	
	2	74		160	
	3	73		189	
	4	75		202	
Site C	1	121		195	
	2	211		228	
	3	218		272	
Site E	1	19	81	67	106
	2	20	80	48	87
	3	33	67	83	77
Site F	1	25	75	73	93
	2	17	83	77	106
Site G	1	36	64	85	81
	2	34	66	81	88
	3	32	68	69	86
AVERAGE (Sites E, F, G)		27	73	73	91
STANDARD DEVIATION		8	8	12	11

*As-Found Ash includes combustible material while Inorganic Ash does not.

Coal Fines. Coal fines were related to particulate loading. It is known that particle entrainment and carryover depends on several variables including particle size, shape, density, and gas velocity. The standard measure of coal fines is the percent by weight passing a 1/4 inch screen. When fitting the data to the mathematical model, it was found that a better correlation was obtained if the criteria for coal fines was percent passing 16 mesh rather than percent passing 1/4 inch. Using 16 mesh as the criteria for coal fines, the following statistical correlations were obtained:

	Δ Particulate, lb/10^6Btu Per 1% Fines Increase	T-Value
Site B	.31	1.75
Site C (Eastern)	.55	3.27
Site E	.22	1.64
Site F	.14	2.62

These data indicate that a 1% increase in coal fines (% passing 16 mesh) results in an average 0.31 lb/10^6Btu particulate loading increase. As with coal ash, this relationship is only valid over the range of data included in the study. Sites A and Cw did not give good correlations, yet these two sites had the highest percentages of coal fines.

3.5.2 Combustibles in the Ash vs. Coal Properties

Combustible content of the boiler outlet flyash and of the bottom ash were evaluated on all six spreader stokers. Coal properties were found to be a factor at two of the test sites. The data from these two sites are presented below. The particular coal property or properties responsible for the differences were not determined.

Test Site C was the stoker which fired both an Eastern bituminous and a Western sub-bituminous coal. The Site C combustible data for both the boiler outlet flyash and the bottom ash are presented in Figures 3-49 and 3-50.

Figure 3-49 shows that the Western coal averaged 10% combustibles in its flyash as compared to 40% for the Eastern coal's flyash. Figure 3-50 shows that the Western coal's bottom ash combustible content was unusually high at reduced loads. This may be due to the Western coals high moisture content.

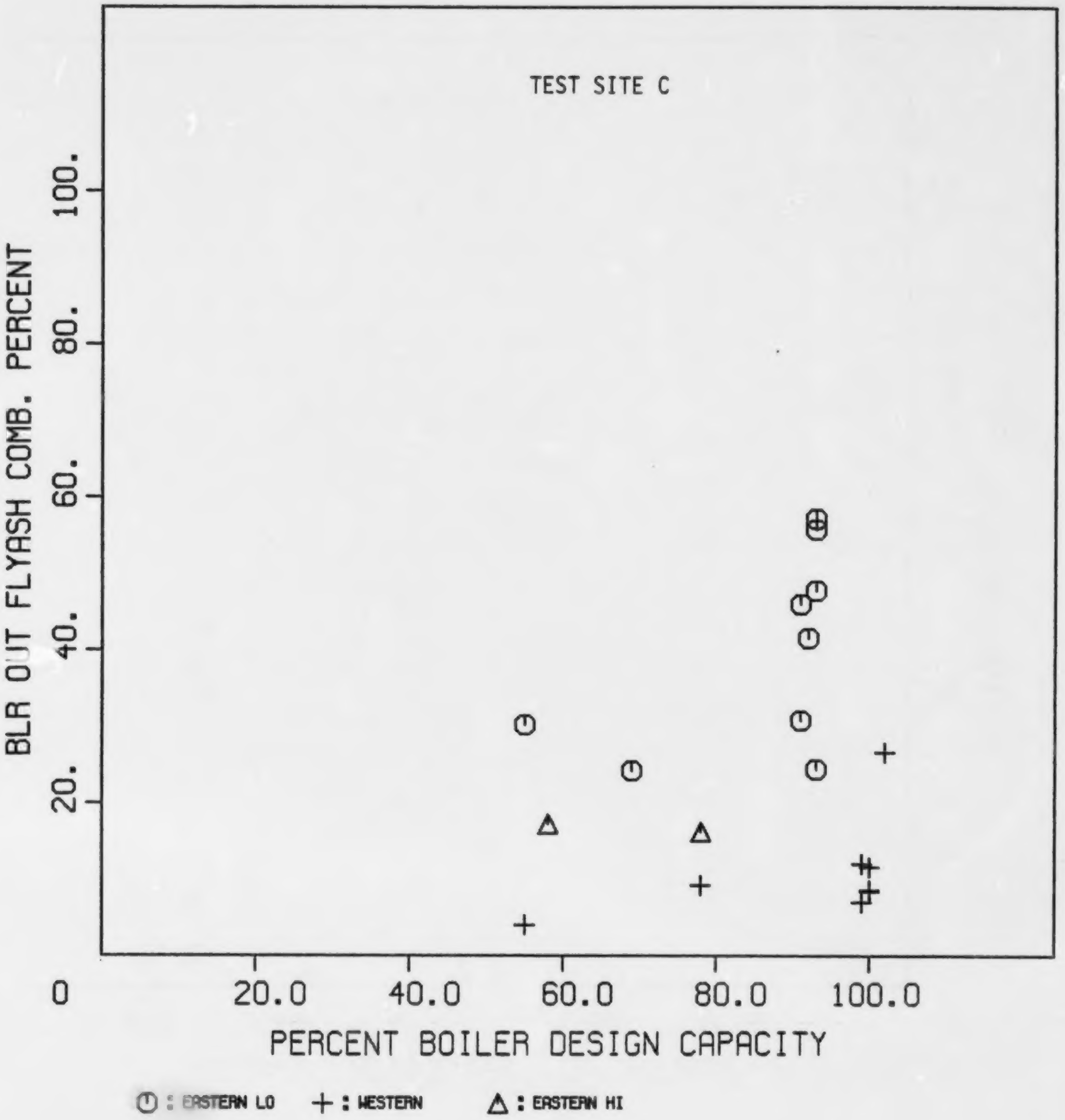

FIG. 3-49
BLR OUT FLYASH COMB. VS. PERCENT DESIGN CAPACITY

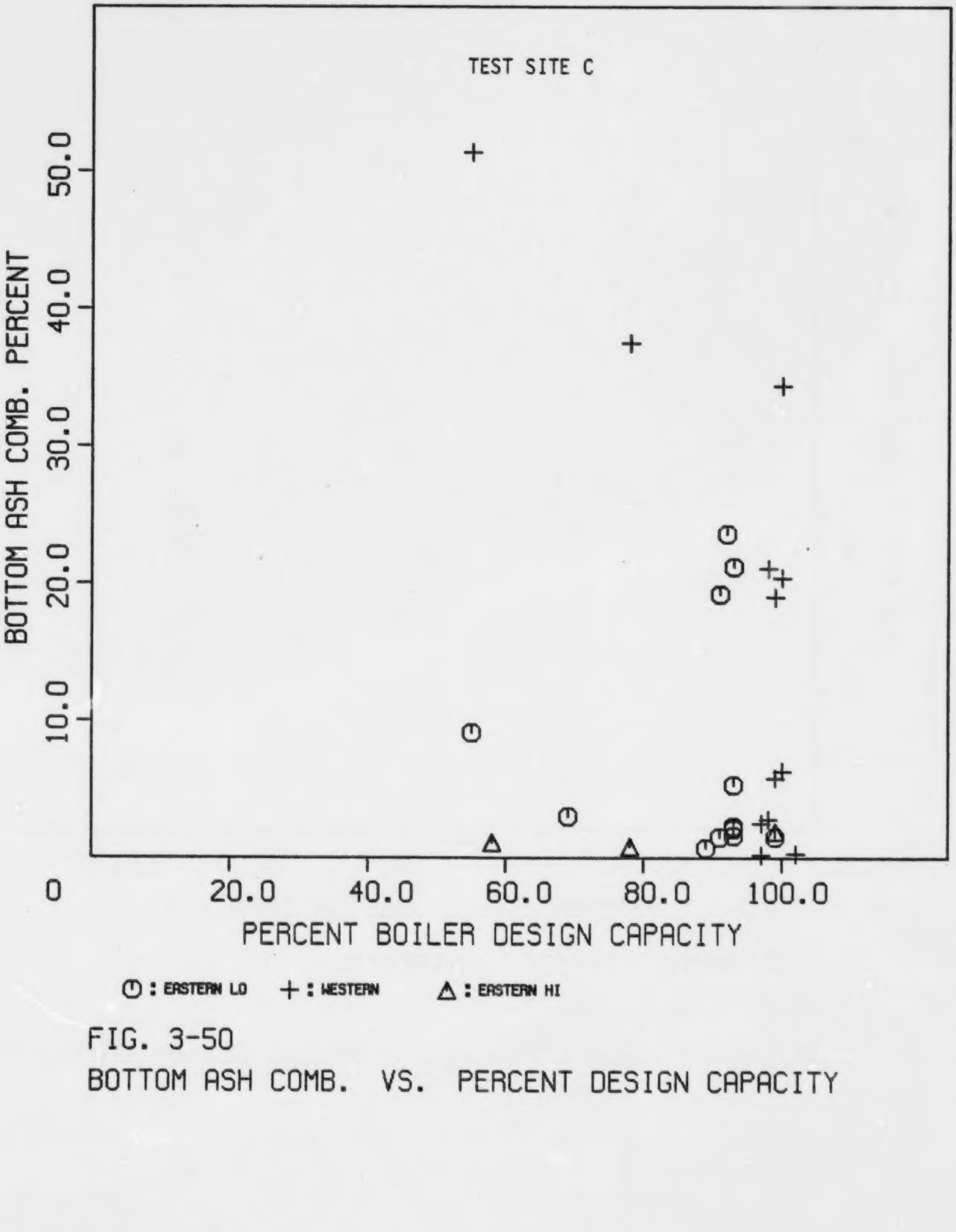

FIG. 3-50

BOTTOM ASH COMB. VS. PERCENT DESIGN CAPACITY

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Test Site B also exhibited some combustible data which could be related to coal properties. However, at this site, the four test coals were nearly identical. Figure 3-51, the Site B flyash combustible data, shows the Hatfield coal data to be somewhat lower than the data from the other coals. Figure 3-52, the Site B bottom ash combustible data, shows the Reload coal data to be consistently low.

3.5.3 Sulfur Oxides vs. Coal Properties

The sulfur dioxide (SO_2) and sulfur trioxide (SO_3) data are presented in a series of plots. Figure 3-53 relates the sulfur oxides in the flue gas to the sulfur in the coal. Both are presented in units of lb/10^6Btu as SO_2 so as to be directly comparable. The plot shows that a relationship exists, as would be expected, but that inaccuracies are present in the data. It is not known if these inaccuracies stem from the coal analysis or the sulfur oxides analysis.

Perhaps a better method of determining the fate of fuel sulfur is to measure the sulfur retained in the ash directly. These data are summarized in Table 3-24. The data indicates that between 1% and 6% of the fuel sulfur is retained in the ash. The high sulfur retention in the Western coal's ash at Site C is likely related to this coal's high calcium content (see Table 3-21).

Sulfur trioxide (SO_3) was found in concentrations of zero to 10 parts per million. This represents zero to 2% of the total sulfur oxides emitted. Sulfur trioxide is plotted as a function of total sulfur oxides emitted in Figure 3-54.

3.5.4 Nitric Oxide vs. Coal Properties

An investigation was made of the relationship between fuel nitrogen and nitric oxide emissions. No direct relationship was found.

The nitric oxide models previously developed in Section 3.3.5 were used to sort out the known relationships of heat release rate and excess air. The differences between the measured NOx and those calculated by the mathematical model were then plotted as a function of fuel nitrogen. The plot for the Site A data is shown in Figure 3-55. No relationship is evident. Plots for the other sites were similar.

A correlation was also attempted by adding a fuel nitrogen factor to the mathematical model. Again, there was no direct correlation.

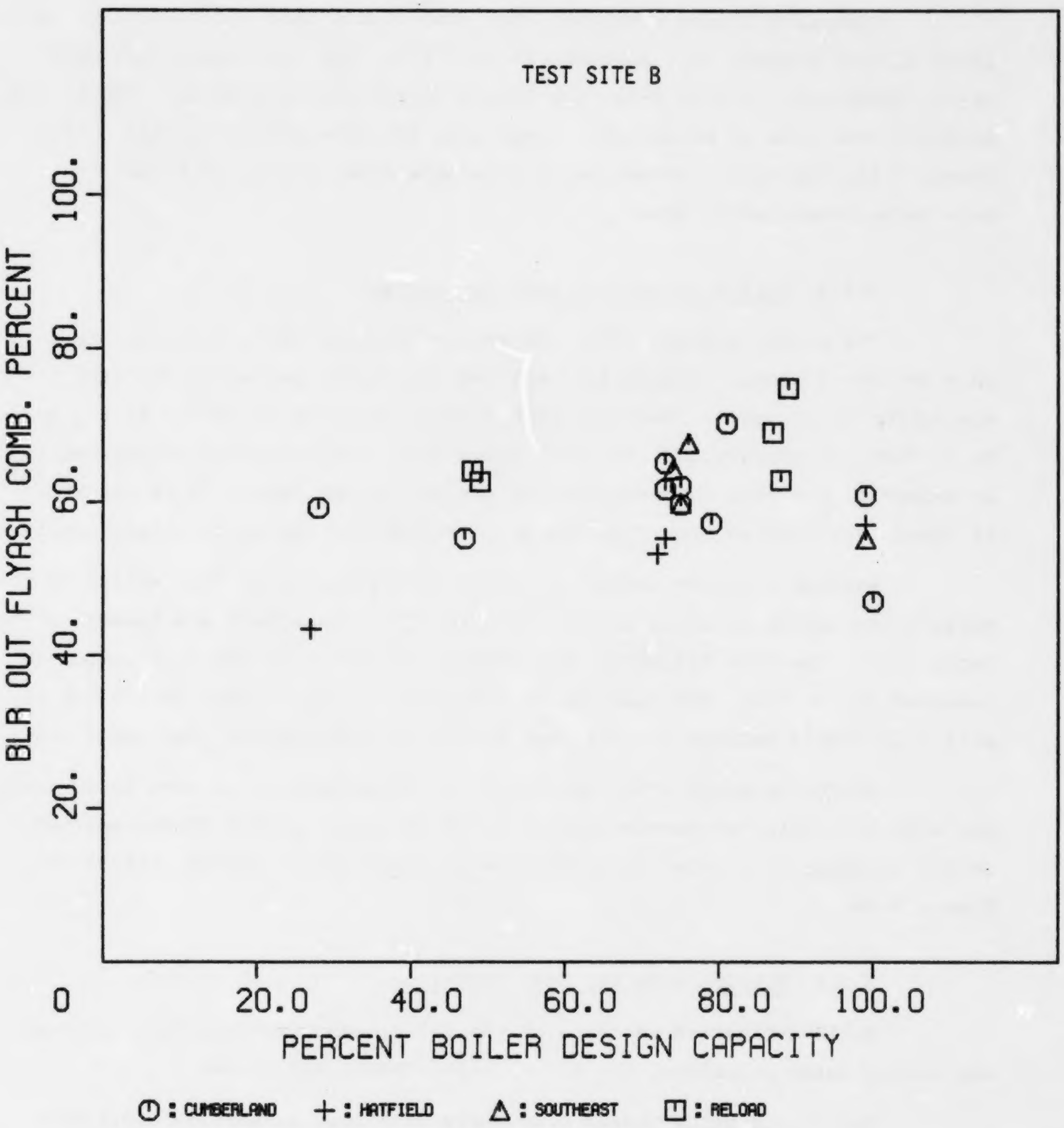

FIG. 3-51

BLR OUT FLYASH COMB. VS. PERCENT DESIGN CAPACITY

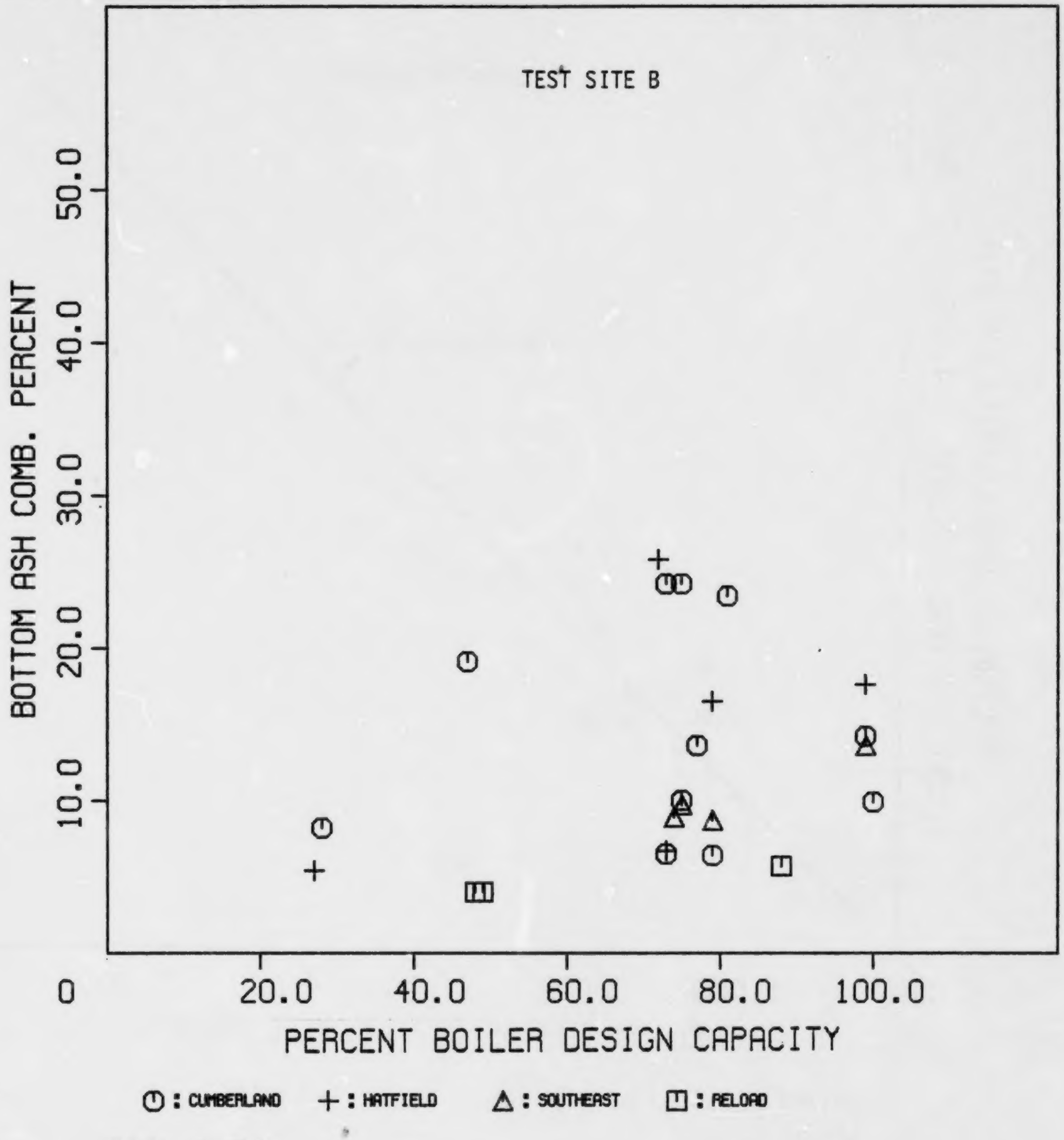

FIG. 3-52
BOTTOM ASH COMB. VS. PERCENT DESIGN CAPACITY

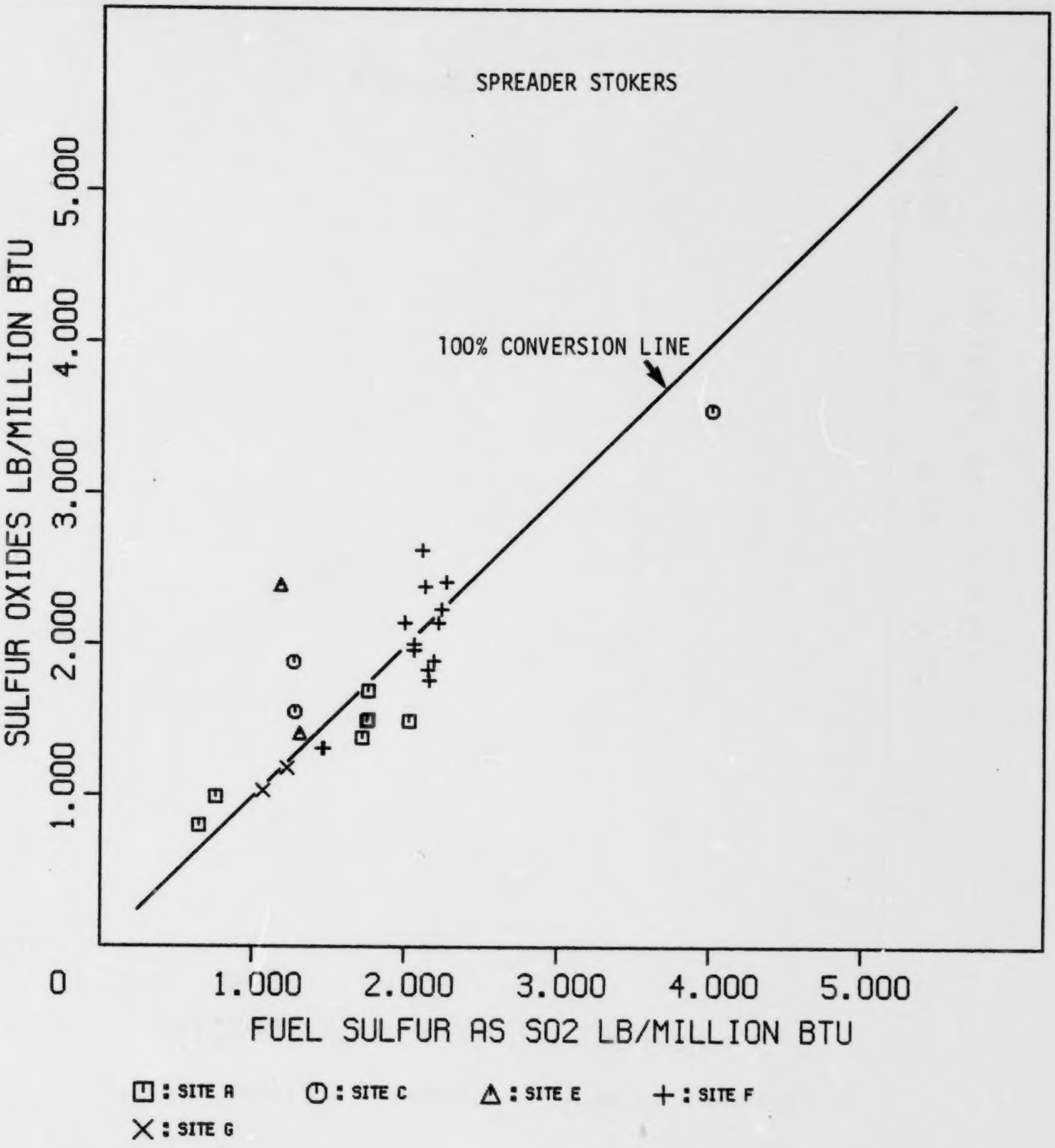

FIG. 3-53
SULFUR OXIDES VS. FUEL SULFUR AS SO2

4-15900-554

TABLE 3-24

SULFUR RETAINED IN THE ASH

	Coal	% Retained in Flyash	% Retained in Bottom Ash	Total
Site A	1	--	0.5	--
	3	2.5	0.3	2.8
Site B	1	1.6	0.1	1.7
	2	0.9	0.3	1.2
	3	1.6	0.1	1.7
Site C	1	4.6	1.5	6.1
	2	12.2	3.4	15.6
Site E	1	1.7	0.7	2.4
	3	3.0	0.6	3.6
Site F	1	3.6	0.5	4.1
	2	3.4	0.7	4.1
Site G	1	5.2	0.6	5.8
	3	3.0	0.6	3.6
AVERAGE		3.6	0.8	4.4
STANDARD DEVIATION		3.0	0.9	3.9

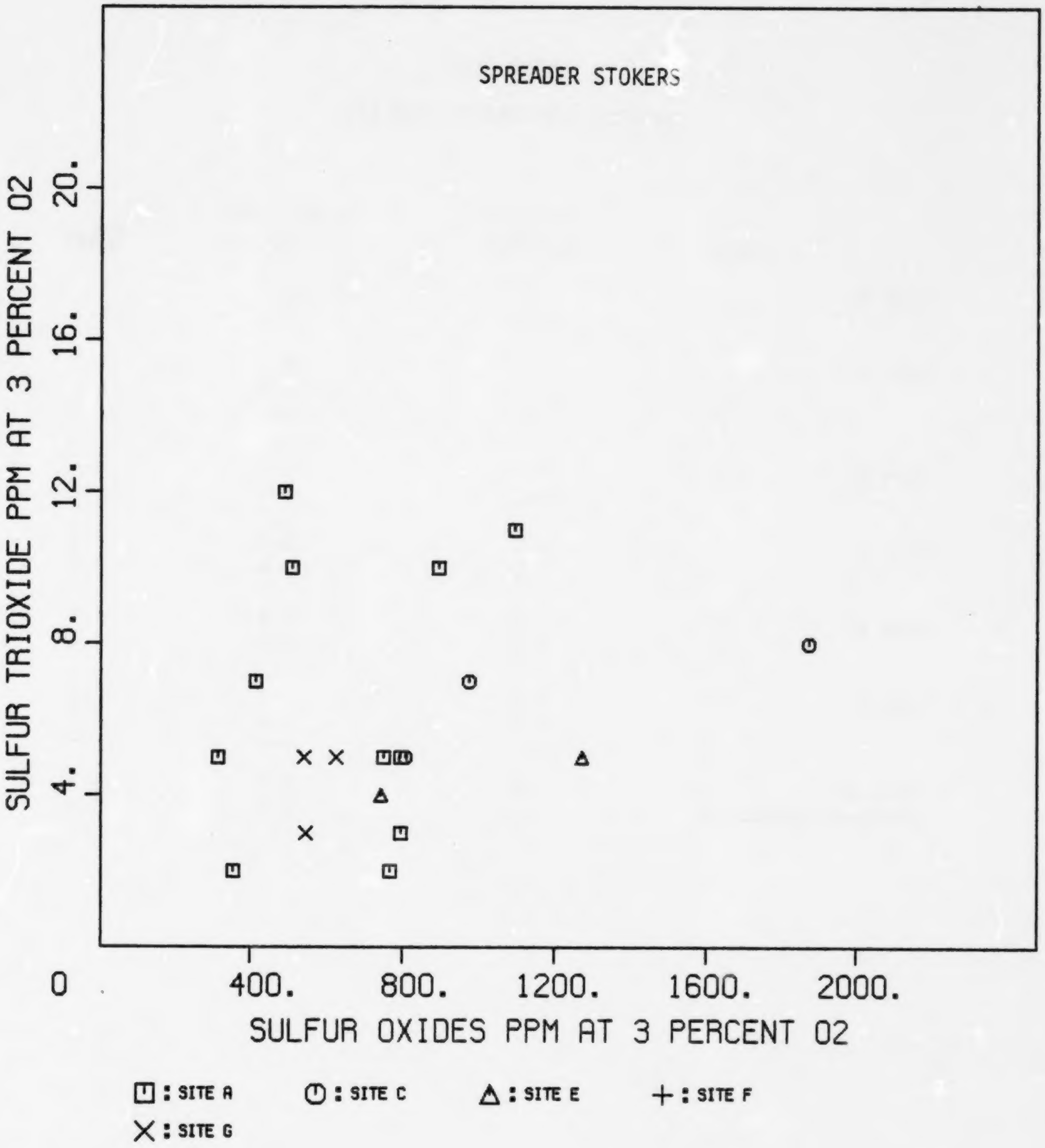

FIG. 3-54
SULFUR TRIOXIDE VS. SULFUR OXIDES

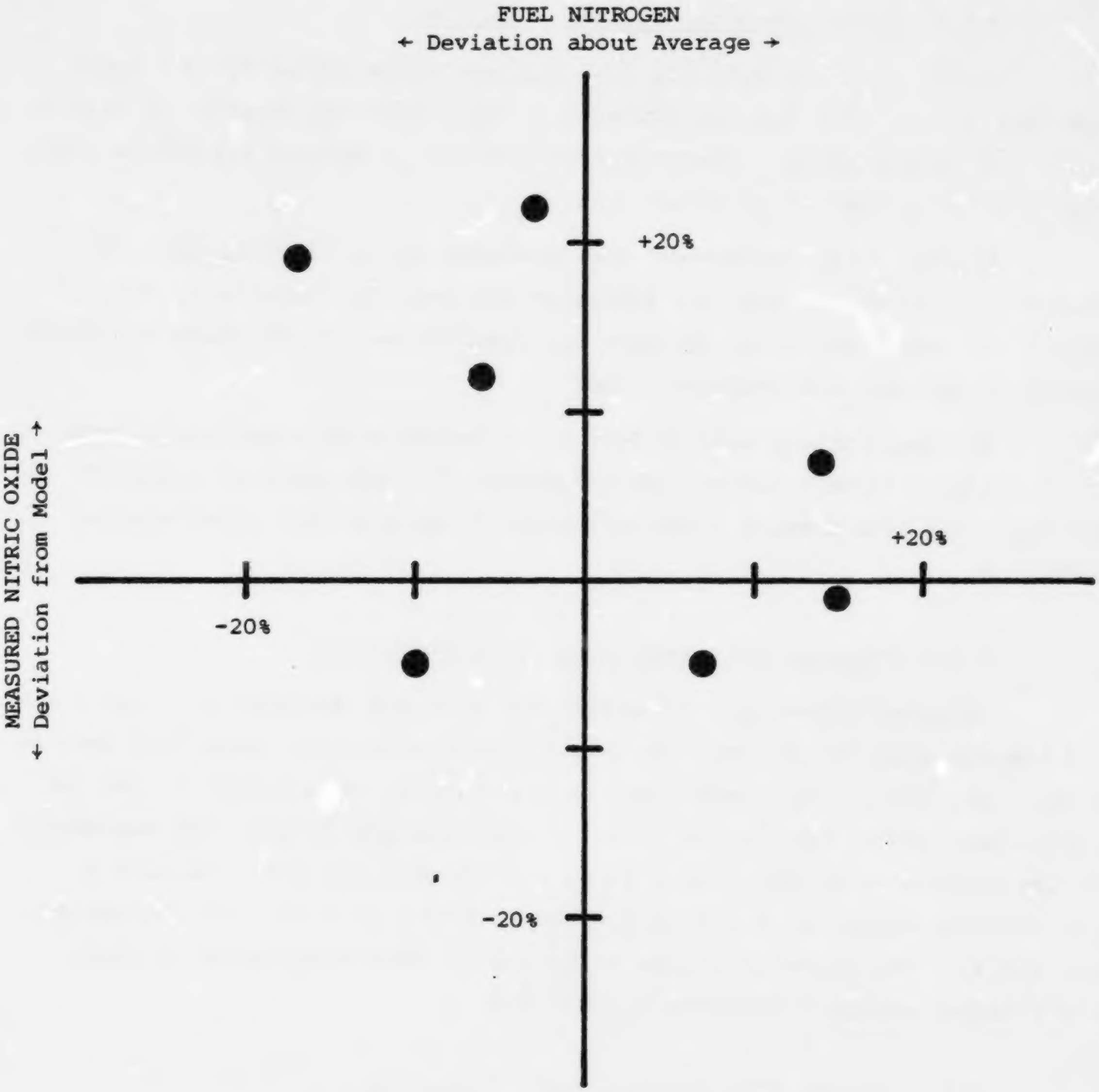

Figure 3-55. Data from Test Site A Indicates that there is no Discernable Relationship between Nitric Oxide Emissions and Fuel Nitrogen.

3.5.5 Carbon Monoxide vs. Coal Properties

Carbon monoxide emissions were greatest while firing Western sub-bituminous coals. The clearest evidence of this trend was observed at Site C which fired both a Western sub-bituminous coal and an Eastern bituminous coal. These data are presented in Figure 3-56.

At full load, the Western coal produced carbon monoxide emissions ranging from 163 to 702 ppm, and averaging 342 ppm. By comparison, when Eastern coal was fired under the same test conditions, the CO emissions ranged from 33 to 263 ppm, and averaged 71 ppm.

The observations made at Site C are supported by observations made at Site A. Site A fired a Western sub-bituminous coal and produced higher CO emissions than Site B which fired an Eastern bituminous coal under similar conditions.

3.5.6 Unburned Hydrocarbons vs. Coal Properties

Unburned hydrocarbon emissions (HC) were only measured at Sites F and G of the six spreader stokers. At Site F the HC emissions ranged from zero to 23 parts per million by volume (ppm) on a wet basis, and averaged 9 ppm. At Site G, they ranged from 19 ppm to 41 ppm and averaged 31 ppm. One explanation for the difference is that Site F fired a lower volatile coal than Site G (29% volatile matter at Site F versus 41% at Site G on a dry, mineral-matter-free basis). The higher volatiles at Site G may have contributed to this site's higher unburned hydrocarbon emissions.

3.5.7 Boiler Efficiency vs. Coal Properties

Moisture and hydrogen in the coal were instrumental in determining boiler efficiency at Test Site C. Boiler efficiency was 3-4% lower while burning a high-moisture Western coal than while burning a low-moisture Eastern coal. The data for Site C are presented in Table 3-25 and Figure 3-57. Coal properties did not differ enough to play a significant role at the other spreader stoker sites.

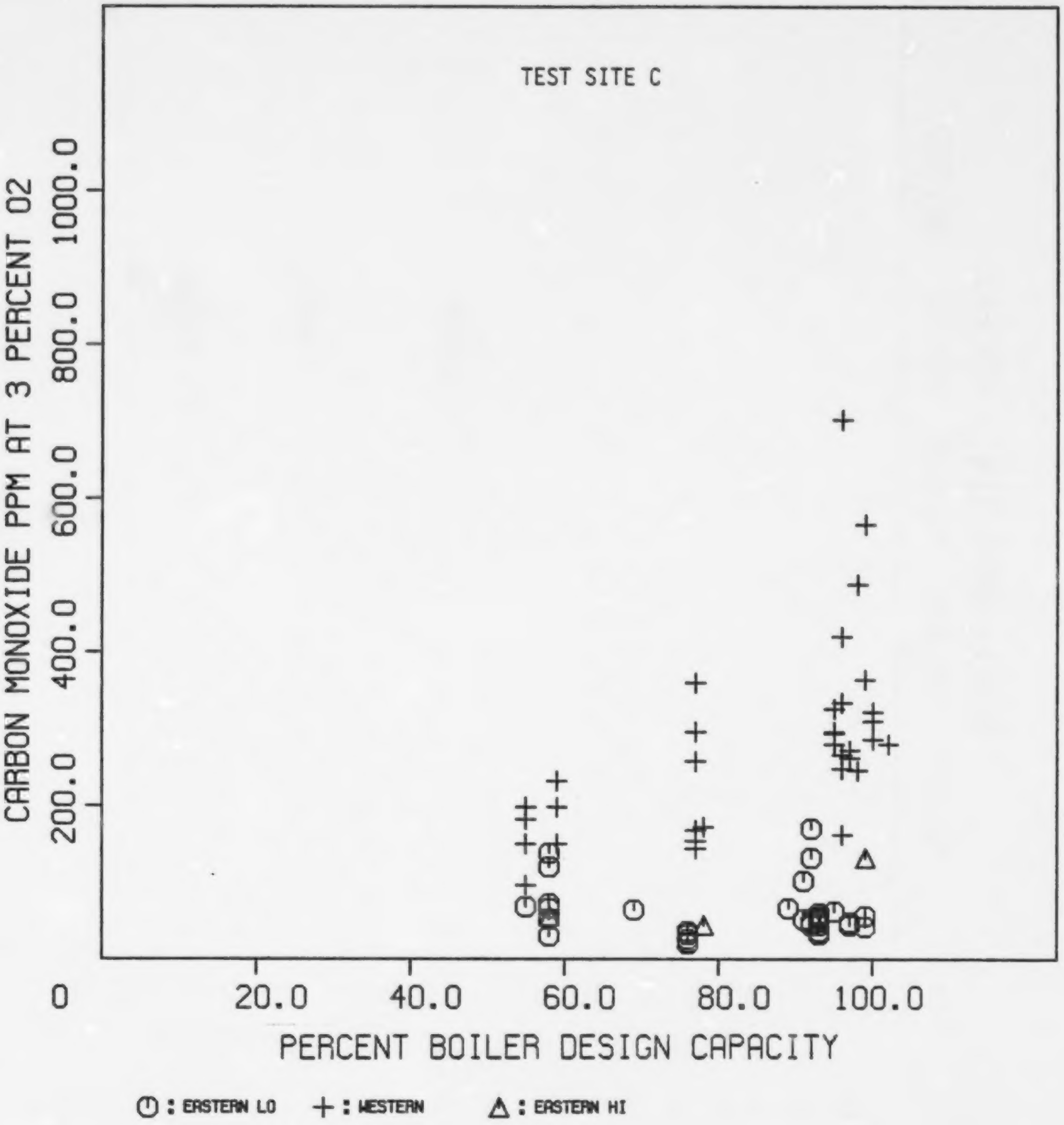

FIG. 3-56

CARBON MONOXIDE VS. PERCENT DESIGN CAPACITY

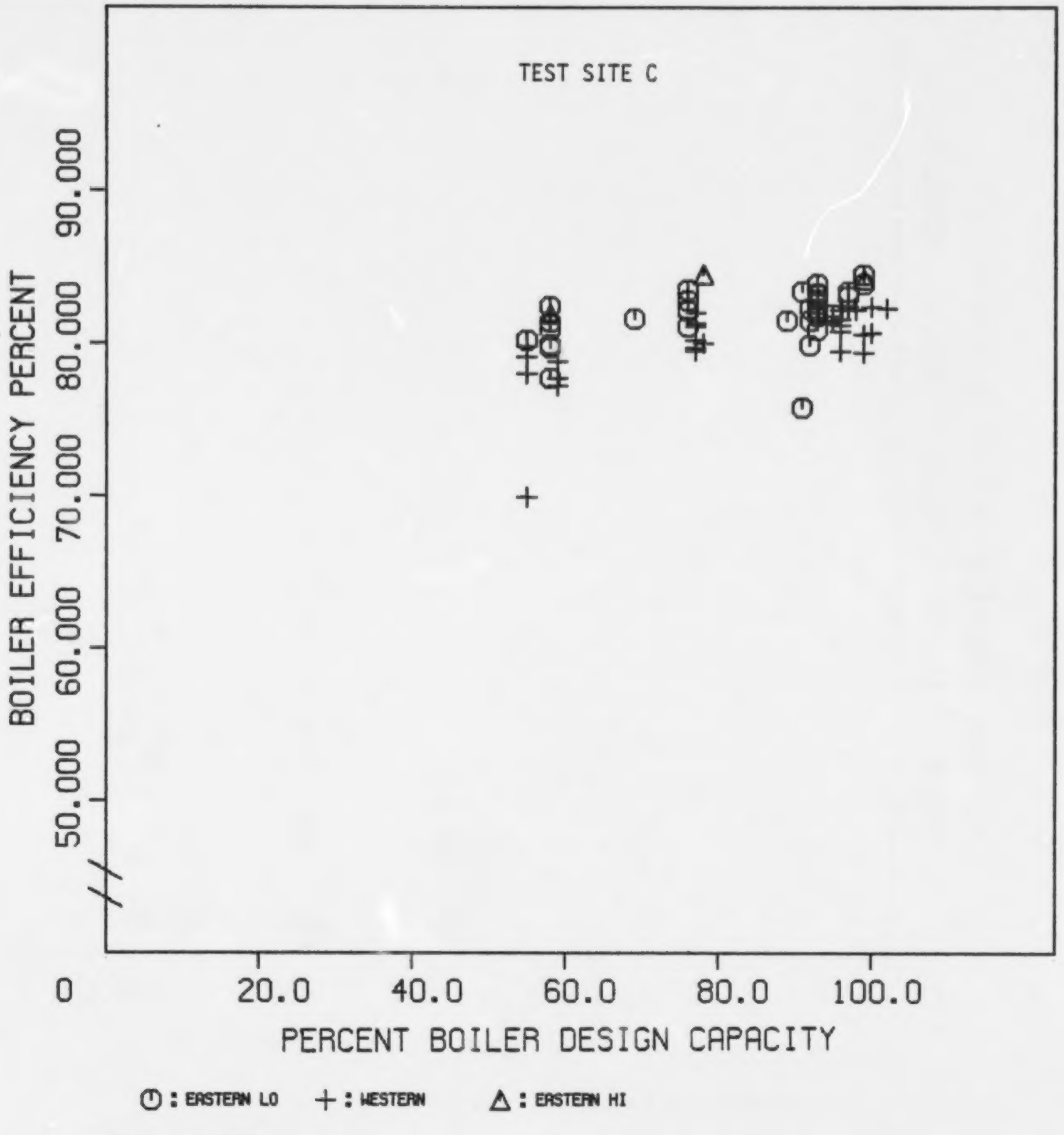

FIG. 3-57
BOILER EFFICIENCY VS. PERCENT DESIGN CAPACITY

4-15900-554

TABLE 3-25

Coal	AVERAGE HEAT LOSSES AT SITE C, PERCENT Dry Gas	Moisture in Fuel	H_2O From H_2 in Fuel	Total Combustibles	Radiation & Unmeasured	BOILER EFFICIENCY PERCENT
Eastern Low Fusion	8.22	0.51	4.50	3.25	1.98	81.56
Western	7.95	3.51	6.25	1.71	1.96	78.63
Eastern High Fusion	8.57	0.89	4.56	1.33	2.08	82.57

3.6 RESPONSE TO OVERFIRE AIR

Overfire air was studied as an operating variable to determine its impact on boiler emissions and efficiency. On each unit, the overfire air pressures were increased and decreased over their range of operation. At Test Site C, overfire air was also biased in different ways to determine in which row of jets it was most effective. Modifications to the overfire air systems were not included in the scope of this program.

The overfire air configurations of the six spreader stokers studied are illustrated in Figures 3-1 through 3-6 of Section 3.0, "Description of Units Tested". Though each was different, the systems had many similarities. All six had both upper and lower rows of jets on the rear water wall. The rear upper jets were situated 5.6 to 6.1 feet above the grate and inclined downward between 0° and 11°. The rear lower jets were situated 1.0 to 2.2 feet above the grate and inclined downward between 0° and 5°.

The arrangement of air jets on the front water wall was peculiar to each stoker manufacturer. All but Site G had front upper jets situated 6.0 to 7.8 feet above the grate and inclined downward by 15° to 26°. Test Site G did not have front upper overfire air jets. Most had front lower jets situated under the feeders and often an integral part of the feeder. These jets were about 18 inches above the grate and were inclined horizontally.

The purpose of overfire air in stoker boilers is to promote complete combustion. This is accomplished by supplying turbulence to the flame zone to better mix the air and volatiles, and by holding the flame away from the cold water walls thereby preventing premature quenching of the flame. When applied correctly, overfire air minimizes the products of incomplete combustion, namely smoke, carbon monoxide, and unburned hydrocarbons. It also allows operation at reduced excess air levels which boosts boiler efficiency. In general, overfire air systems are designed to supply 15 to 20% of the total combustion air.

3.6.1 Particulate Loading vs. Overfire Air

Uncontrolled particulate loading was observed to decrease when overfire air pressures were increased in the vast majority of tests. This result is considered significant even though the mechanism accounting for the reduction was not identified. The data are presented in Table 3-26. The Test Site A data are plotted in Figure 3-58.

Combustible burnout accounted for all of the particulate reduction in one test and was a factor in two others. In most tests, however, the inorganic ash portion of the particulates was also reduced. Reductions in coal fines, an uncontrolled variable, could account for only three cases of particulate reductions. Therefore, the turbulence induced by the overfire air apparently prevented some of the particles from being carried over. Particulate reductions as high as 53% resulted from increasing the overfire to undergrate air ratio while holding other known variables constant.

Test Site G was the only site where increasing the overfire air pressure resulted in increased particulate loading, and this is supported by only one test set. It is possible that the lower air jets at Site G were kicking up ash from the grate. The lower rear jets were inclined toward the grate by 5° and were operated at pressures of up to 23" H_2O gauge. It is also noted that Site G was the only site without front upper air jets. These Site G observations should not be the basis for any conclusions since the data is scant, but it was felt that these observations should be recorded. One must also keep in mind that overfire air systems are not designed for the purpose of controlling particulate loading.

At Test Site C, the overfire air pressures were biased in different directions. By this we mean that they were increased in one area and decreased in another area while keeping the total overfire air flow roughly constant. These variations at Site C had no significant impact on particulate loading. For example, when most of the overfire air was put through the upper air jets

TABLE 3-26

EFFECT OF OVERFIRE AIR ON UNCONTROLLED PARTICULATE LOADING
SPREADER STOKERS

			UNCONTROLLED PARTICULATE LOADING - LB/10^6Btu						
Site	Coal	% Design Capacity	Low OFA	High OFA	Percent Change	Other Overfire Air Conditions			
A	2	85	20.48	15.41	-25				
	3	76	20.48	11.89	-42				
	3	60	13.26	6.29	-53				
B	1	48	11.75	9.98	-15				
	2	73	12.27	9.25	-25				
	4	80	9.57	7.21	-25				
						Bias Upper	Bias Lower	Bias Front	Bias Rear
C (E)	1	92	21.11	19.02	-10	20.88	22.63	23.86	25.14
C (W)	2	99	31.14	29.22	- 6	33.99	31.59	33.09	36.42
						Bias Front	Bias Upper	High Front* Medium Rear	
E	1	64	ND	4.49	ND	4.32	5.23	2.06	
						Baseline High Front Med Rear			
F	1	100	8.79	6.14	-30	5.51			
G	1	83	4.33	4.27	- 1				
	3	77	4.00	4.57	+14				

* Test is suspect because particulate loading is disproportionately low.

ND = No data

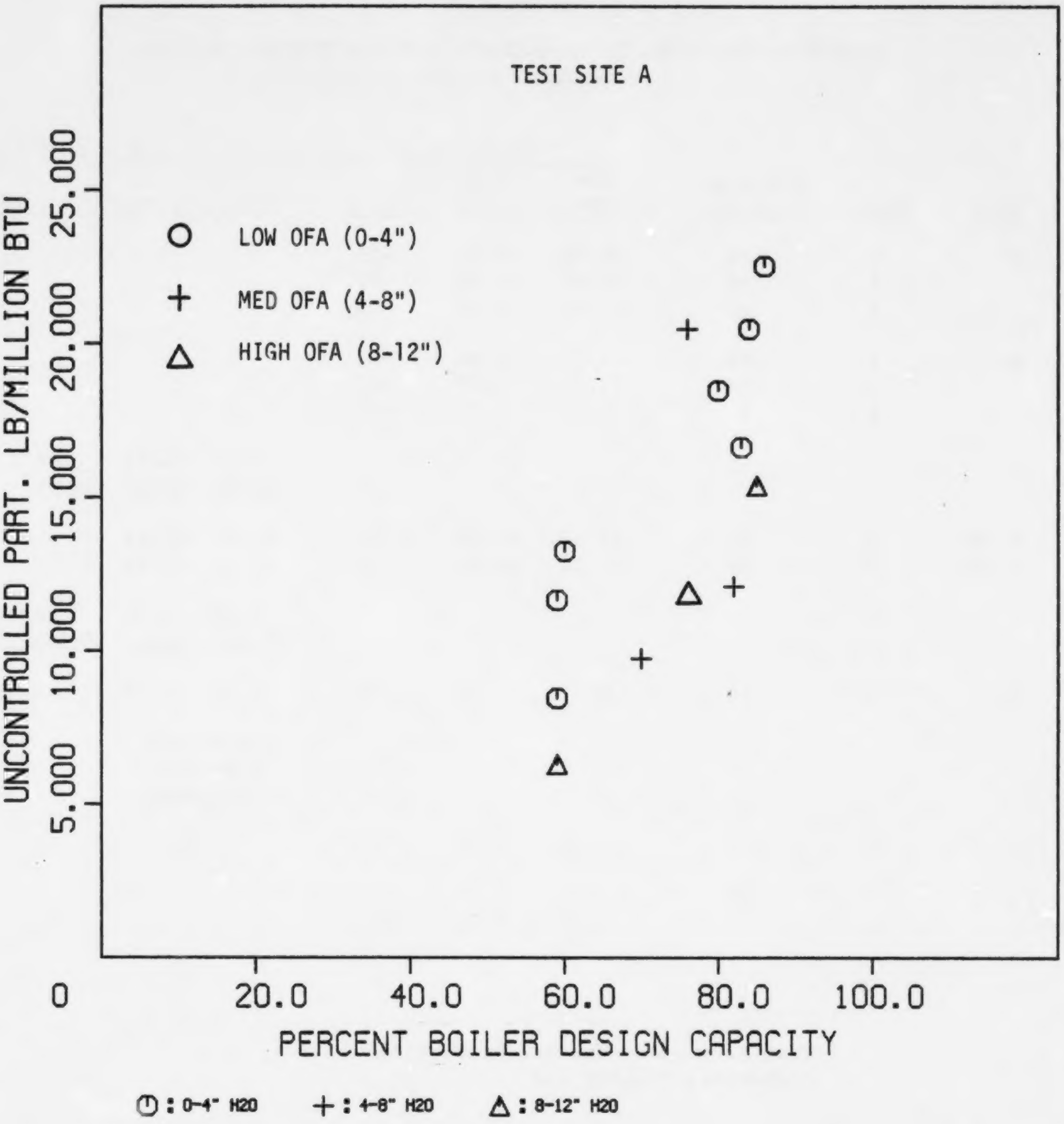

FIG. 3-58
UNCONTROLLED PART. VS. PERCENT DESIGN CAPACITY

(Bias Upper) as opposed to putting most of the air through the lower jets (Bias Lower), particulate loading increased 8% in one set of tests on Western coal and decreased 8% on one set of tests on Eastern coal. This is interpreted as normal data scatter. Similarly, biasing the air to the front jets as opposed to biasing the rear air jets resulted in increases of 5% and 10% in the uncontrolled particulate loading. Again, these results may not be significant due to normal data scatter.

3.6.2 Combustibles in the Ash vs. Overfire Air

The percentage of combustible material in the flyash increased more often than it decreased when overfire air pressures were increased. This surprising result is not necessarily a trend. As with all tests conducted during this program there were many uncontrolled variables which could have biased the results.

Although increased overfire air did not reduce the percentage of combustible material in the flyash, it did reduce the rate at which flyash was carried over and this in turn led to a reduced carbon carryover and a reduced combustible heat loss. The effect of overfire air on boiler efficiency is discussed in Section 3.6.6. The combustible data are presented in Table 3-27.

3.6.3 Nitric Oxide vs. Overfire Air

Overfire air is used in burner-fired combustion devices to produce staged combustion. This technique is an effective nitric oxide control strategy on burner-fired combustion devices.

The term "overfire air", when applied to stokers, is something entirely different, and was designed for a different purpose. Nevertheless, overfire air on stokers can in theory be used to produce a limited degree staged combustion and this aspect was investigated.

The test results, summarized in Table 3-28, show that increasing the overfire air to undergrate air ratio at constant excess air has no significant effect on nitric oxide emissions. It was not possible to set up the degree of staged combustion necessary for NOx reduction. Limiting factors were clinkering and overheating of the grate as the undergrate air is reduced, and the limited capacity of the overfire air jets. The test results show small increases in

TABLE 3-27

EFFECT OF OVERFIRE AIR ON COMBUSTIBLES IN FLYASH SPREADER STOKERS

			PERCENT COMBUSTIBLE MATERIAL IN FLYASH						
Site	Coal	% Design Capacity	Low OFA	High OFA	Percent Change	Other Overfire Air Conditions			
A	2	85	65.8	54.6	-17				
	3	76	70.0	66.6	- 5				
	3	60	47.2	61.3	+30				
B	1	80	57.3	70.3	+23				
	2	73	53.3	55.2	+ 4				
	4	48	62.6	64.0	+ 2				
						Bias Upper	Bias Lower	Bias Front	Bias Rear
C (E)	1	92	30.8	47.8	+55	24.4	46.0	55.9	41.6
C (W)	2	99	ND	8.7	ND	12.1	11.7	7.1	ND
						Bias Front	Bias Upper	High Front Medium Rear	
E	1	64	ND	70.6	ND	58.6	75.3	62.3	
						Baseline High Front Med Rear			
F	1	100	71.9	71.4	- 1	70.1			
G	1	83	52.2	58.1	+11				
	2	77	62.9	50.6	-20				

ND = No Data

TABLE 3-28

EFFECT OF OVERFIRE AIR ON NITRIC OXIDE EMISSIONS
SPREADER STOKERS

			NITRIC OXIDE - LB/10^6Btu*						
Site	Coal	% Design Capacity	Low OFA	High OFA	Percent Change	Other Overfire Air Conditions			
A	2	85	.718	.715	0				
	3	76	.541	.500	- 8				
	3	60	.559	.539	- 4				
B	4	48	.374	.400	+ 7				
	2	73	.371	.469	+26				
	1	80	.478	.465	- 3				
						Bias Upper	Bias Lower	Bias Front	Bias Rear
C (E)	1	92	.330	.391	+18	.439	.448	.454	.463
C (W)	2	99	.533	.562	+ 5	.522	.527	.584	.602
						Bias Front	Bias Upper	High Front Medium Rear	
E	1	64	ND	.552	ND	.548	.597	.614	
F	1	100	.401	.358	-11				
G	1	83	.483	.394	-18				
	3	77	.488	.573	+17				

* Both tests in each data set have been corrected to a common excess oxygen level to eliminate the effects of this variable.

ND = No Data

NOx during five test sets, small decreases in NOx during five test sets, and no change during one test set. These variations are ascribed to normal data scatter.

The tests at Site C, in which overfire air was biased in several directions, shown the lowest NOx when most of the overfire air is passed through the upper jets, and the highest NOx when the overfire air is passed through the jets on the rear wall. The implication is that the lower rear jets, which are most effective in reducing carbon monoxide, also tend to increase NOx on this unit.

3.6.4 Carbon Monoxide vs. Overfire Air

Carbon monoxide emissions were reduced by the increased use of overfire air in these tests. Table 3-29 shows the carbon monoxide test results.

Carbon monoxide was significantly reduced at Test Sites A, C, and F by increasing overfire air pressure. This is an indication that the turbulence created by overfire air is helping to complete combustion. Figure 3-59 shows the effects of low overfire air at Site F.

At Site B, the carbon monoxide emissions were very low under all overfire air conditions tested. The increase from 36 to 96 ppm at this site is not considered very significant. More significant are the changes in the larger emission levels such as the 55% reduction at Site A when CO dropped from 1076 to 480.

Test Site E had very little CO data and Site G had no CO data due to problems with the carbon monoxide monitor.

3.6.5 Unburned Hydrocarbons vs. Overfire Air

Test Site F was the only location where unburned hydrocarbons were evaluated as a function of overfire air conditions. No clear data trends were observed. The data are presented below.

TABLE 3-29

EFFECT OF OVERFIRE AIR ON CARBON MONOXIDE EMISSIONS
SPREADER STOKERS

			CARBON MONOXIDE, PPM (DRY) AT 3% O_2						
Site	Coal	% Design Capacity	Low OFA	High OFA	Percent Change	Other Overfire Air Conditions			
A	2	85	1076	480	-55				
	3	76	313	300	- 4				
	3	60	670	61	-91				
B	1	80	44	47	+ 7				
	2	73	103	34	-67				
	4	48	36	96	+167				
						Bias Upper	Bias Lower	Bias Front	Bias Rear
C (E)	1	92	103	53	-49	49	53	37	44
C (W)	2	99	488	311	-36	395	287	567	323
						Bias Front	Bias Upper		
E	1	64		No Data		62	147		
						Baseline			
F	1	100	378	163	-57	228			
			607	429	-29	382			
G	1	83		No Data					
	3	77							

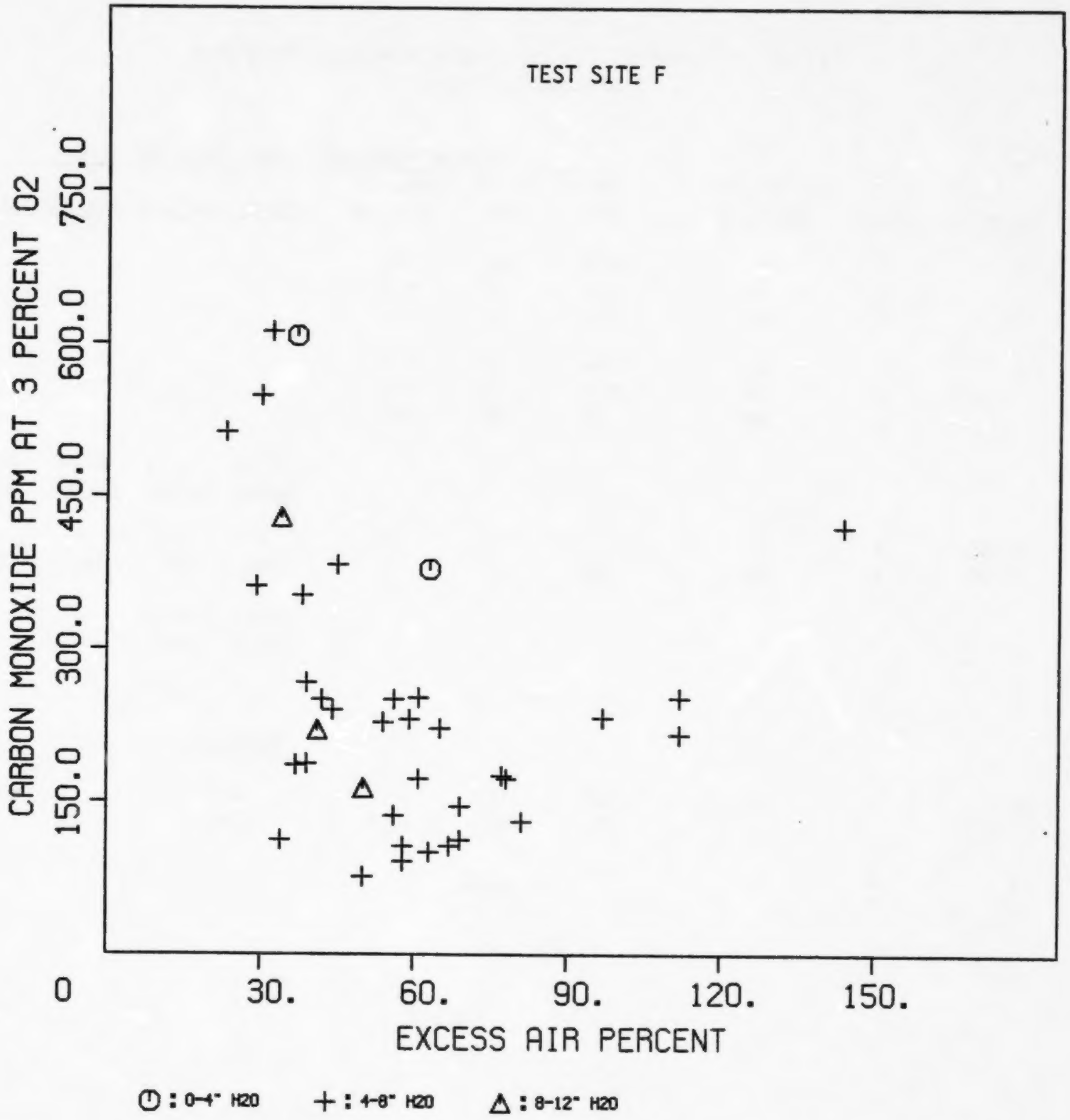

FIG. 3-59
CARBON MONOXIDE VS. EXCESS AIR

% Design Capacity	Excess Air, %	UNBURNED HYDROCARBONS, PPM (WET) Low OFA	 Baseline OFA	 High OFA
100	56	0	13	13
99	39	16	9	5

3.6.6 Boiler Efficiency vs. Overfire Air

Boiler efficiency was improved by an average 1% when overfire air pressures were increased. This efficiency gain is the result of reduced carbon carryover. As noted earlier, the percentage of combustibles in the ash was not reduced but the particulate loading was reduced and this in turn reduced the carbon carryover.

Table 3-30 presents the changes in the individual heat loss categories which were determined for each overfire air test set. Many of the changes such as fuel moisture and H_2O from H_2 are coal related. The radiation losses are load related, and the dry gas losses are related more to excess air than to overfire air. The dominating heat loss change appears in the flyash combustible category and this is believed to be a direct result of the increase in overfire air pressure.

TABLE 3-30

EFFECT OF OVERFIRE AIR ON HEAT LOSSES AND EFFICIENCY SPREADER STOKERS

		CHANGE IN PERCENT HEAT LOSS WHEN OVERFIRE AIR INCREASED						
Site	Coal	Dry Gas	Fuel Moisture	H_2O From H_2	Flyash Combustibles	Bottom Ash Combustibles	Radiation	Change In Boiler Efficiency
A	2	.29	-.10	.02	-1.96	-.02	.00	1.77
	3	-.45	-.01	-.03	-1.80	-.04	.00	2.33
	3	-.06	.00	.00	- .66	-.14	.01	.85
B	1	-.37	.06	-.04	.29	.76	.00	-.70
	2	1.21	-.10	-.01	-2.93	-1.68	-.02	3.53
	4	.83	-.26	-.21	- .38	- .06	.02	.06
C (E)	1	-.26	-.02	-.22	-2.82	- .33	-.02	3.67
C (W)	2	.11	-.05	.13	.88	.11	.00	-1.18
E	1	-.28	-.23	.01	-1.37	- .86	.04	2.69
F	1	-1.41	-.22	-.07	-2.76	- .42	.00	4.88
G	1	1.39	.04	.22	.32	.89	-.04	-2.82
	3	1.01	.06	.07	- .30	- .04	.02	-.82
AVERAGE		.17	-.07	-.01	-1.12	- .15	.00	1.19
STD. DEV.		.82	.11	.12	1.33	.67	.02	2.33

3.7 RESPONSE TO DEGREE OF FLYASH REINJECTION

Three of the six spreader stokers tested, Sites A, B and C, were equipped for flyash reinjection from their mechanical dust collectors. The degree of reinjection was either reduced or stopped completely on each of these units to determine what effect this had on emissions and efficiency. A similar test was conducted at Site F which was equipped for reinjection from its economizer hopper. The following subsections describe the tests and the results obtained. The test data are summarized in Table 3-31.

It is worth noting that all six spreader stokers reinjected flyash from their boiler hoppers, and two of them reinjected flyash from an air heater or an economizer. All used pneumatic reinjection systems, as opposed to the gravity feed type.

3.7.1 Test Description - Site A

Site A is a 300,000 lb/hr spreader stoker equipped for flyash reinjection from the boiler hoppers, air heater hoppers and mechanical dust collector hoppers. Site A is also equipped with the option of diverting the mechanical collector flyash to a surge hopper from which it is discarded. This arrangement made it very convenient to run performance tests on the flyash reinjection system at Site A.

The procedure for diverting the flyash into the surge hopper was very simple. Sliding gate valves were located on the downcommers from the dust collector hopper immediately below the high pressure venturies and reinjection lines. The gate valves were opened and the reinjection air pressure was reduced as much as possible by closing butterfly valves in the air supply lines. This allowed much of the flyash to fall into the surge hopper.

Some of the flyash from the mechanical collector hopper may still have been reinjected when the gate valves were opened. Unfortunately, there was no way of measuring the rates at which flyash was collected or reinjected in this configuration without going to considerable expense. Thus, there is no quantitative data on the percentage reduction in rejected flyash obtained at Site A.

Two successful test sets were conducted in which a full reinjection test and a reduced reinjection test were run back-to-back. It was felt that

TABLE 3-31

SUMMARY TABLES FOR FLYASH REINJECTION
TEST SETS ON SITES A, B AND C

	SITE A		SITE A		SITE B		SITE C			SITE C		
Reinjection Configuration	Blr Hpr Air Htr	Blr Hpr Air Htr 100% D.C.	Blr Hpr Air Htr	Blr Hpr Air Htr 100% D.C.	Blr Hpr* 42% D.C.	Blr Hpr* 60% D.C.	None	Blr Hpr	Blr Hpr* 70% D.C.	None	Blr Hpr	Blr Hpr* 70% D.C.
FIRING CONDITIONS												
Load, % of Capacity	82	83	59	59	99	100	93	93	89	98	102	98
Excess Air, %	26	23	29	26	34	32	72	72	70	60	62	67
Coal Classification	Sub-Bituminous		Sub-Bituminous		Bituminous		Bituminous			Sub-Bituminous		
Coal Sizing, % passing ¼"	45	70	67	49	36	25	43	50	52	49	46	42
Coal Ash, %	2.65	2.63	2.92	2.86	2.60	10.66	10.73	10.81	12.01	8.50	8.56	8.20
UNCONTROLLED EMISSIONS												
Particulate Loading, lb/10^6Btu	12.1	16.6	8.4	11.7	9.6	15.8	6.0	7.0	25.0	8.6	6.1	31.1
Combustible Loading, lb/10^6Btu	8.7	9.7	5.1	5.1	5.8	7.4	--	4.0	--	--		--
Inorganic Ash Loading lb/10^6Btu	3.4	6.9	3.3	6.6	3.8	8.4	--	3.0	--	--		--
Combustibles in Flyash, %	72.1	58.4	60.8	43.7	60.9	47.0	--	57.2	--	--	26.6	--
Combustibles in Bottom Ash, %	--	--	0.5	0.3	14.2	9.9	2.3	1.6	0.7	2.8	0.3	21.1
O_2, % (dry)	4.5	4.1	4.8	4.4	5.5	5.3	9.1	9.1	8.9	8.1	8.3	8.7
CO, ppm (dry) @ 3% O_2	998	1600	150	104	41	60	55	53	66	247	280	488
NO, lb/10^6Btu	0.524	0.492	0.504	0.525	0.343	0.431	0.514	0.486	0.421	0.507	0.483	0.520
CONTROLLED EMISSIONS												
Particulate Loading, lb/10^6Btu	--	--	--	--	0.49	0.60	0.48	0.50	0.82	0.52	0.47	1.03
Combustible Loading, lb/10^6Btu	--	--	--	--	0.13	0.15	0.11	0.14	0.14	0.07	0.06	0.06
Inorganic Ash Loading lb/10^6Btu	--	--	--	--	0.36	0.45	0.37	0.35	0.67	0.45	0.41	0.96
Combustibles in Flyash, %	--	--	--	--	26.7	25.0	23.6	28.9	17.4	13.7	12.4	6.2
Combustibles in Discarded Ash %	76.7	--	--	--	79.5	56.7	21.6	40.9	32.6	9.3	17.6	3.8
Dust Collector Efficiency, %	--	--	--	--	95.0	96.3	92.0	92.9	96.7	93.9	92.4	96.7
COMBUSTIBLE HEAT LOSSES												
Emitted Flyash	0.57	0.72	0.36	0.35	0.24*	0.24*	0.15	0.19	0.21*	0.11	0.09	0.10*
Discarded Flyash	2.30	0.00	1.46	0.00	8.09*	6.76*	2.32	3.86	3.43*	1.20	1.45	0.50*
Bottom Ash	--	--	0.01	0.01	1.01	0.64	0.15	0.10	0.05	0.20	0.02	1.44
TOTAL Combustible in Refuse	2.87	0.72	1.83	0.36	9.34	7.64	2.62	4.15	3.69	1.51	1.56	2.04

* The percentage of ash reinjected from the dust collectors at Sites B and C was not measured. Instead, combustible heat loss calculations are based on design data.

test variables could be minimized by conducting both tests on the same day.

A third test set was not entirely successful. The unit tripped out briefly during the test due to a low drum water level. Although testing was stopped until the load was restored, the load continued to fluctuate drastically during the remainder of the test. The results of this questionable test are not included in Table 3-31.

3.7.2 Test Description - Site B

Site B is a 200,000 lb/hr spreader stoker equipped for pneumatic flyash reinjection from its boiler hopper and selective type dust collector. The selective type dust collector has two hoppers and internal baffles which are designed to segregate the particles by size so that only the larger particles are reinjected. By design, 60% of the collected ash is reinjected. No practical method was found for verifying this percentage. The actual percentage may vary significantly from the design 60%.

During one test, the mechanical dust collector reinjection rate was reduced, and emissions were measured. The reduction was accomplished by extending a pipe from the bottom of each reinjection line into a sealed drum. Reinjection air pressure was reduced to near zero but the lines were not capped off. Therefore, some of the ash was reinjected and some was collected in the drums. In this manner, the reinjection rate was reduced without dismantling the reinjection hardware.

Ash was collected at a rate of 460 lb/hr over a 2-1/2 hour period. This represents 30% of the calculated normal reinjection rate, or a 30% reduction in the reinjection rate from the mechanical dust collector.

A second test was run under similar conditions to the first except that flyash reinjection was not reduced. The results of these two tests are compared in Table 3-31 and in the following discussions.

3.7.3 Test Description - Site C

Site C is a 182,500 lb/hr spreader stoker equipped for pneumatic flyash reinjection from its boiler hopper and selective type dust collector.

Based on design specifications, it is assumed that 70% of the dust collector's ash is reinjected. As with Site B, the actual percentage was not measured.

Unlike Sites A and B, it was possible to completely stop flyash reinjection at Site C, and to accurately measure the ash flow rates. This was accomplished by blocking the venturi at the head of the reinjection line and allowing all of the flyash to drop into tare weighed barrels placed under each downcommer.

Test sets were run on both an Eastern and a Western coal. Each test set consisted of full reinjection, boiler hopper reinjection only, and no reinjection.

3.7.4 Particulate Loading vs Flyash Reinjection

The test results discussed in the following sections will be compared with the published results of a similar study conducted in 1949 by Battelle Memorial Institute.[25] The earlier study involved a 100,000 lb/hr spreader stoker equipped with a gravity reinjection system, while the boilers tested under this program had pneumatic reinjection systems.

Reentrainment of the reinjected flyash was found to be very significant in our tests. This was evidenced by the significant reductions in particulate loading which accompanied each reduction in reinjection rate. The data, presented in Tables 3-32 and 3-33, show reductions ranging from 27% to 80% at the boiler outlet, and 19% to 54% after the dust collector. Looked at in another way, reinjecting flyash from the mechanical dust collector increased the particulate loading by a factor ranging from 1.4 to 5.1 at the boiler outlet, and by a factor of 1.2 to 2.2 at the dust collector outlet. The Battelle data shows similar reductions in particulate loading brought on by reduced reinjection.

A comparison of the particulate loadings of the spreader stokers with and without reinjection from the mechanical dust collector is especially revealing. The data are tabulated in Table 3-34.

TABLE 3-32

PARTICULATE LOADING DATA FOR FIVE REINJECTION RATE TEST SETS

	Uncontrolled Particulate, lb/10^{6}Btu		Controlled Particulate, lb/10^{6}Btu	
	Reduced Reinjection	Full Reinjection	Reduced Reinjection	Full Reinjection
Site A	12.1	16.6	--	--
Site A	8.4	11.7	--	--
Site B	9.6	15.8	0.49	0.60
Site Ce	6.0, 7.0	25.0	0.48, 0.50	0.82
Site Cw	8.6, 6.1	31.1	0.52, 0.47	1.03

TABLE 3-33

REDUCTION IN PARTICULATE LOADING DUE TO REDUCED REINJECTION RATE

		Boiler Outlet	Collector Outlet
Site A	- High Load	27%	--
	Low Load	28%	--
Site B	- High Load	39%	19%
Site C	- Eastern Coal	72%	39%
	Western Coal	80%	54%
Battelle	- Island Creek Coal	18%	43%
	Illinois #6 Coal	45%	21%

TABLE 3-34

UNCONTROLLED PARTICULATE LOADING AT FULL LOAD

	Test Site	Uncontrolled Particulate Loading $lb/10^6Btu$
Spreaders with Reinj.	A	16.6 - 22.5
	B	12.7 - 15.8
	Ce	19.0 - 28.0
	Cw	29.2 - 36.4
Spreaders w/o Reinj.	Ce	6.0 - 7.0
	Cw	6.2 - 8.6
	E	2.1 - 6.5
	F	5.2 - 8.8
	G	2.9 - 6.8

Site C was tested in both configurations, and whereas it had the highest particulate loading with flyash reinjection, it fell in the same range as Sites E, F, and G when fired without reinjection. This implies that the degree of reinjection is by far the major factor contributing to its excessively high boiler outlet particulate loading. The Test Site C uncontrolled particulate loading data are presented in Figure 3-60 to further illustrate the impact which reinjection rate had on this emission.

3.7.5 Combustibles in the Ash vs. Flyash Reinjection

The percentage of combustible material in the flyash increased when the reinjection rate was decreased. This would indicate that combustibles in the reentrained flyash are being consumed, and the energy recovered. The data are presented in Table 3-35 and Figure 3-61.

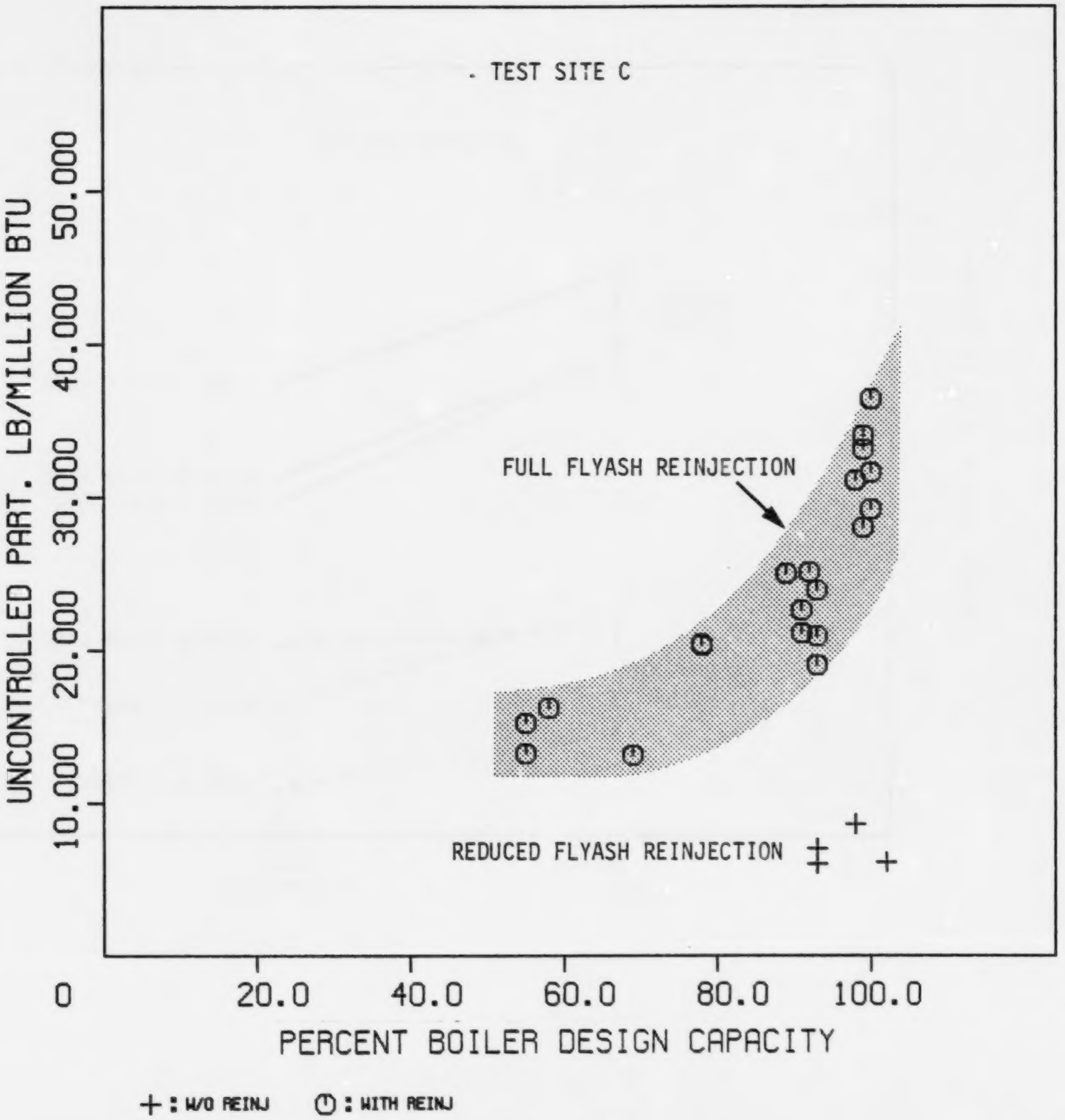

FIG. 3-60
UNCONTROLLED PART. VS. PERCENT DESIGN CAPACITY

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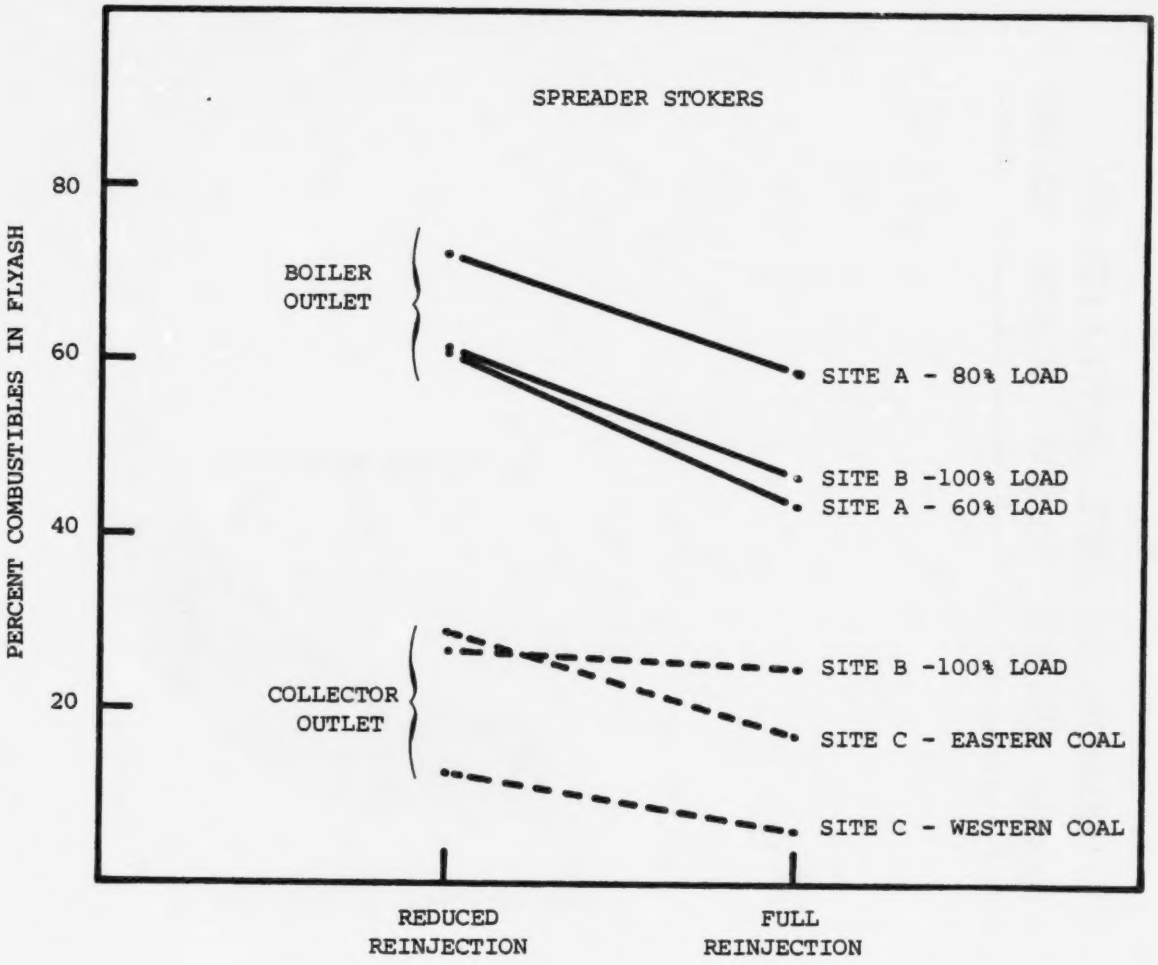

Figure 3-61. Effect of Flyash Reinjection on Combustible Content of Flyash.

TABLE 3-35

INCREASE IN COMBUSTIBLE CONTENT OF FLYASH DUE TO REDUCED REINJECTION RATE

		Boiler Outlet	Collector Outlet
Site A -	High Load	23%	--
	Low Load	39%	--
Site B -	High Load	30%	7%
Site C -	Eastern Coal	--	66%
	Western Coal	--	100%
Battelle -	Island Creek Coal	38%	43%
	Illinois #6 Coal	63%	16%

The recovery rates of the reinjected combustibles were difficult to assess with accuracy. At Site A, the calculated recovery rates for the two test sets were 93% and 100%. This is higher than had been expected. By comparison, the Battelle report concludes that 63% of the reinjected carbon was recovered in their tests. Both results may be accurate, but it is recommended that more research be conducted in this area to establish a broader data base.

There was insufficient data to calculate recovery rates for reinjected combustibles at Sites B and C. This is because they were equipped with selective type dust collectors. On such units it is necessary to know precisely the percentage of collected ash reinjected and the percentage discarded. It is also necessary to know the combustible contents of each fraction. It was not within the scope of this program to build the elaborate setup required to make these measurements.

The difference in flyash combustible heat loss for the two test sets at Site A were 2.15% for the high load test and 1.47% for the low load test. These figures represent the increase in boiler efficiency afforded by the reinjection of flyash from the mechanical dust collector.

3.7.6 Particle Size Distribution vs. Flyash Reinjection

The particle size distribution data for the reinjection test sets are presented in Figures 3-62, 3-63, and 3-64. This data was derived from Bahco classifier tests and sieve analysis of flyash samples collected at the boiler outlet. The data are also presented in Table 3-36 along with dust collector efficiency data.

TABLE 3-36

DUST COLLECTOR EFFICIENCY AND PARTICLE SIZE DISTRIBUTION VS REINJECTION RATE

	Dust Collector Efficiency, %		% Particles Below 10 Micrometers	
	Reduced Reinjection	Full Reinjection	Reduced Reinjection	Full Reinjection
Site B - Eastern Coal	94.9	96.2	8.0	6.0
Site C - Eastern Coal	92.9	96.7	7.7	5.0
Site C - Western Coal	92.4	96.7	9.5	4.8

All three test sets show the same trend. Flyash reinjection reduces the percentage of fine particles and increases the percentage of coarse particles. The largest increases occur with the particles larger than 100 micrometers. This shift in particle size distribution towards the larger particles increases the collection efficiency of the mechanical dust collector by several percent. This increase in dust collector efficiency due to flyash reinjection at Site C is graphically presented in Figure 3-65.

Another method of presenting the particle size distribution data is to combine it with the particulate loading data to create particle size concentration plots. These plots, presented in Figures 3-66, 3-67, and 3-68, show that the greatest increase in particulate loading occurs in the range of 20-300 micrometers. The percentage increase in particulate loading by particle size resulting from increased reinjection is plotted in Figure 3-69 for two of the three test sets. The trend is consistent.

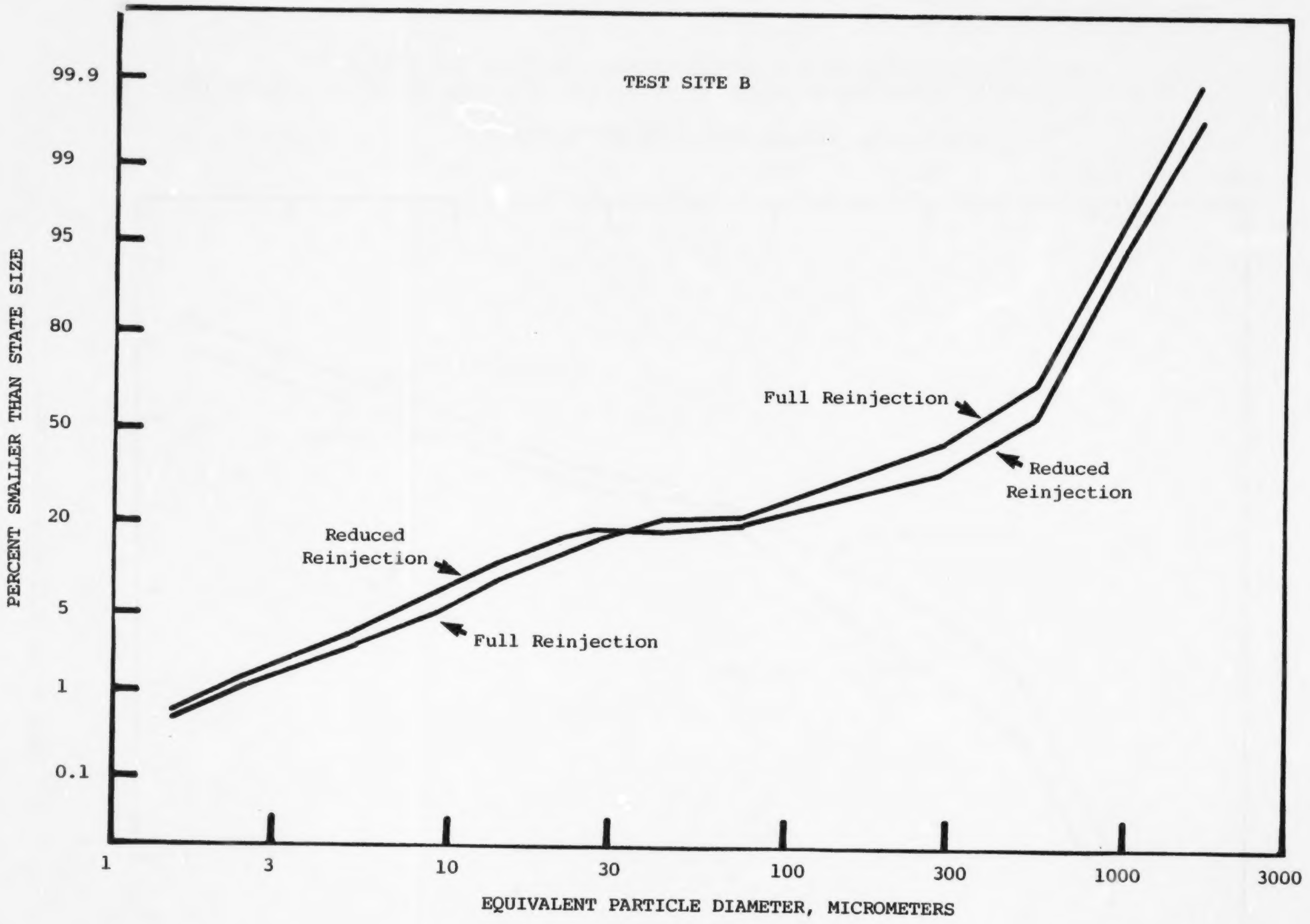

Figure 3-62. Particle Size Distribution of Flyash at Boiler Outlet of Site B for Case of Full and Reduced Reinjection from the Mechanical Dust Collector.

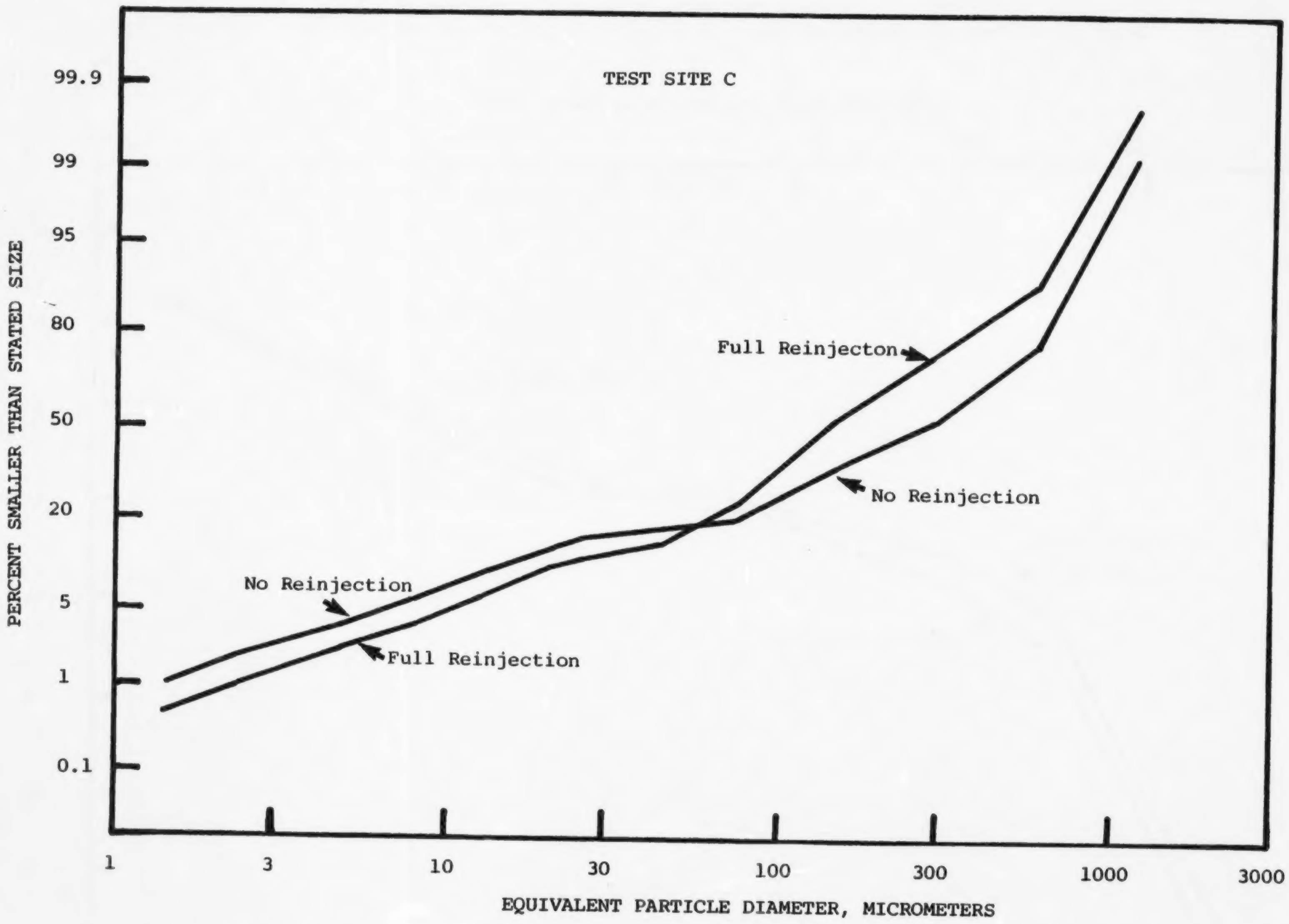

Figure 3-63. Particle Size Distribution of Flyash at Boiler Outlet of Site C for Case of Full and Reduced Reinjection While Firing Eastern Coal.

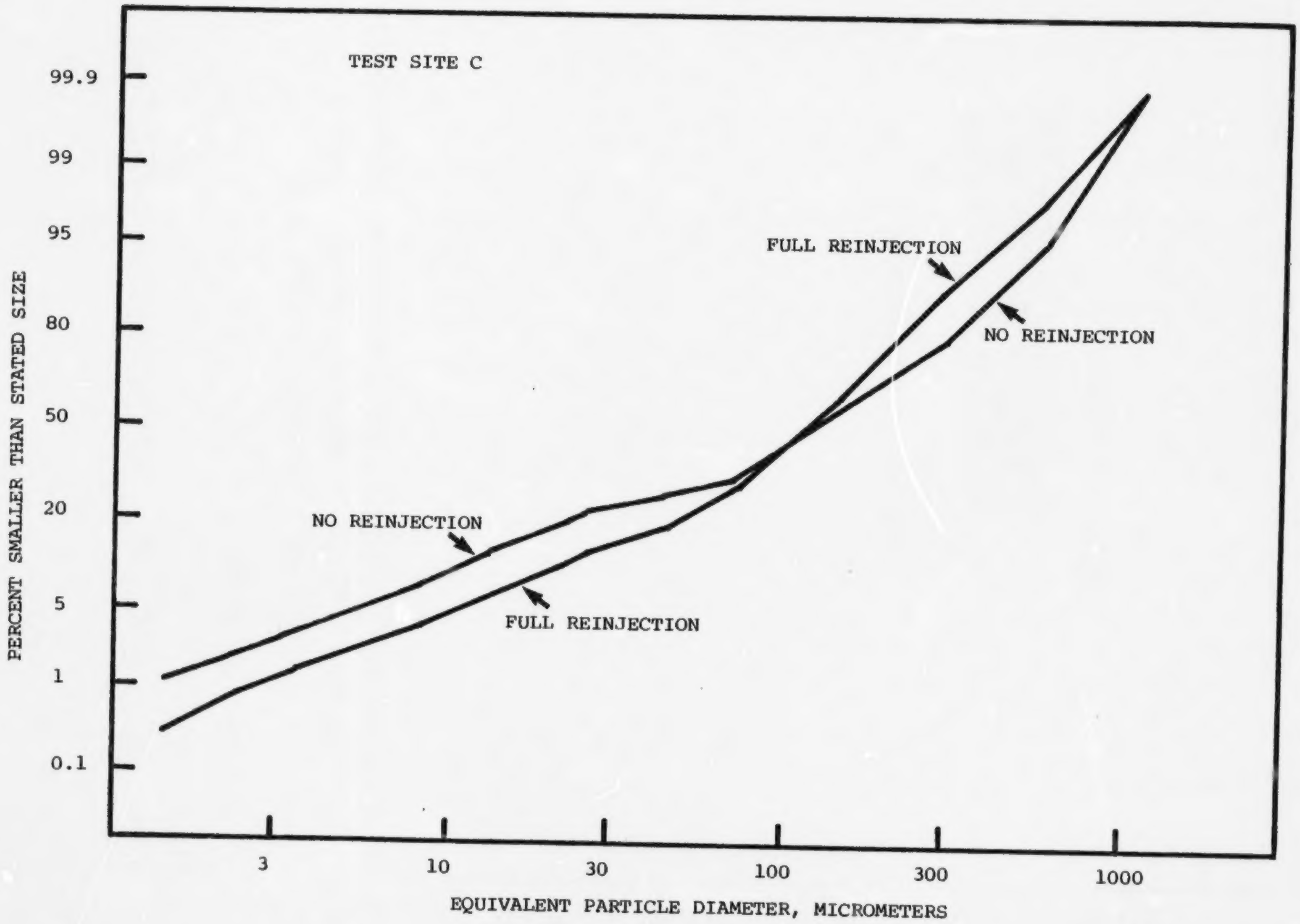

Figure 3-64. Particle Size Distribution of Flyash at Boiler Outlet of Site C for Case of Full and Reduced Reinjection While Firing Western Coal.

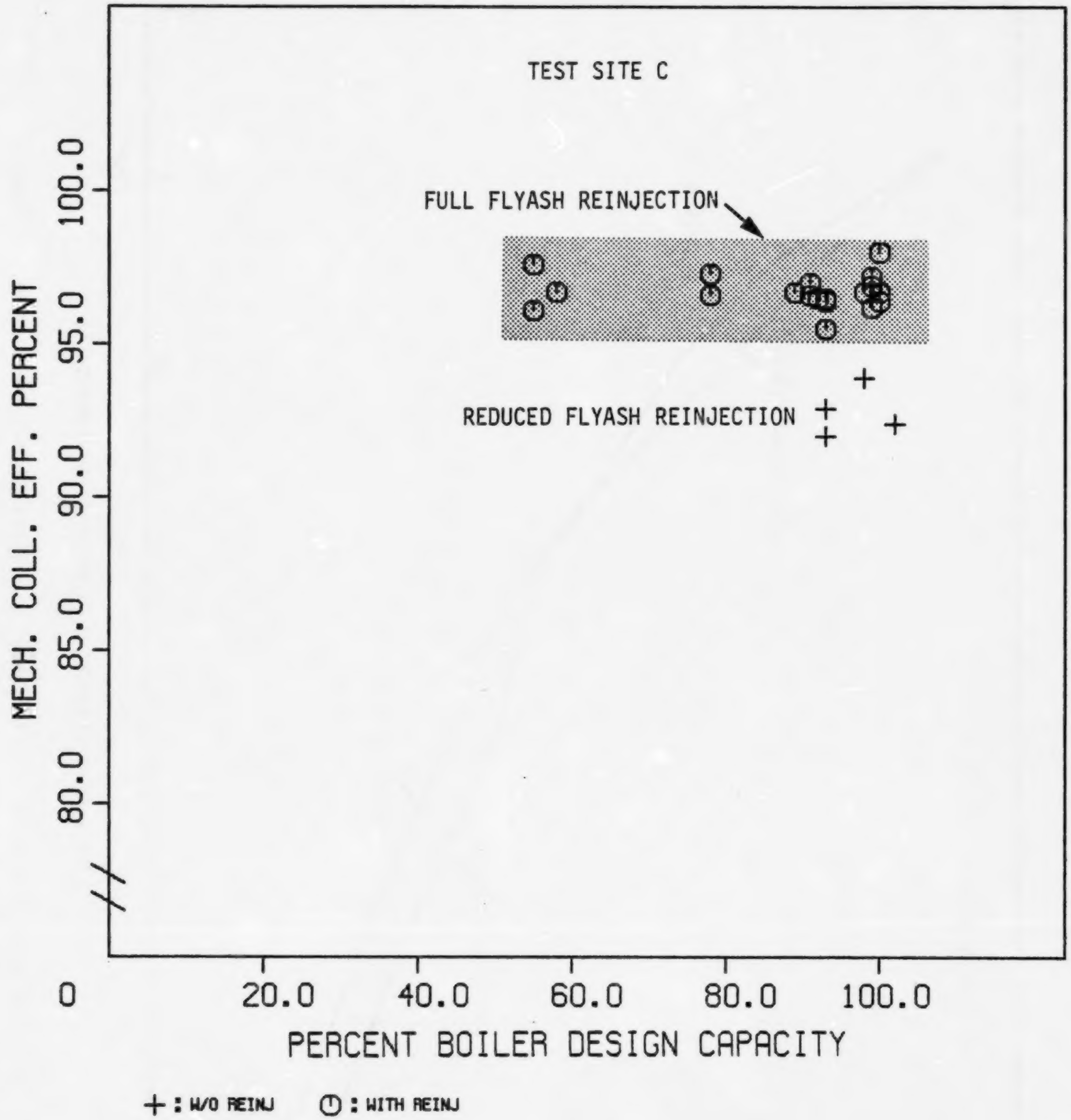

FIG. 3-65
MECH. COLL. EFF. VS. PERCENT DESIGN CAPACITY

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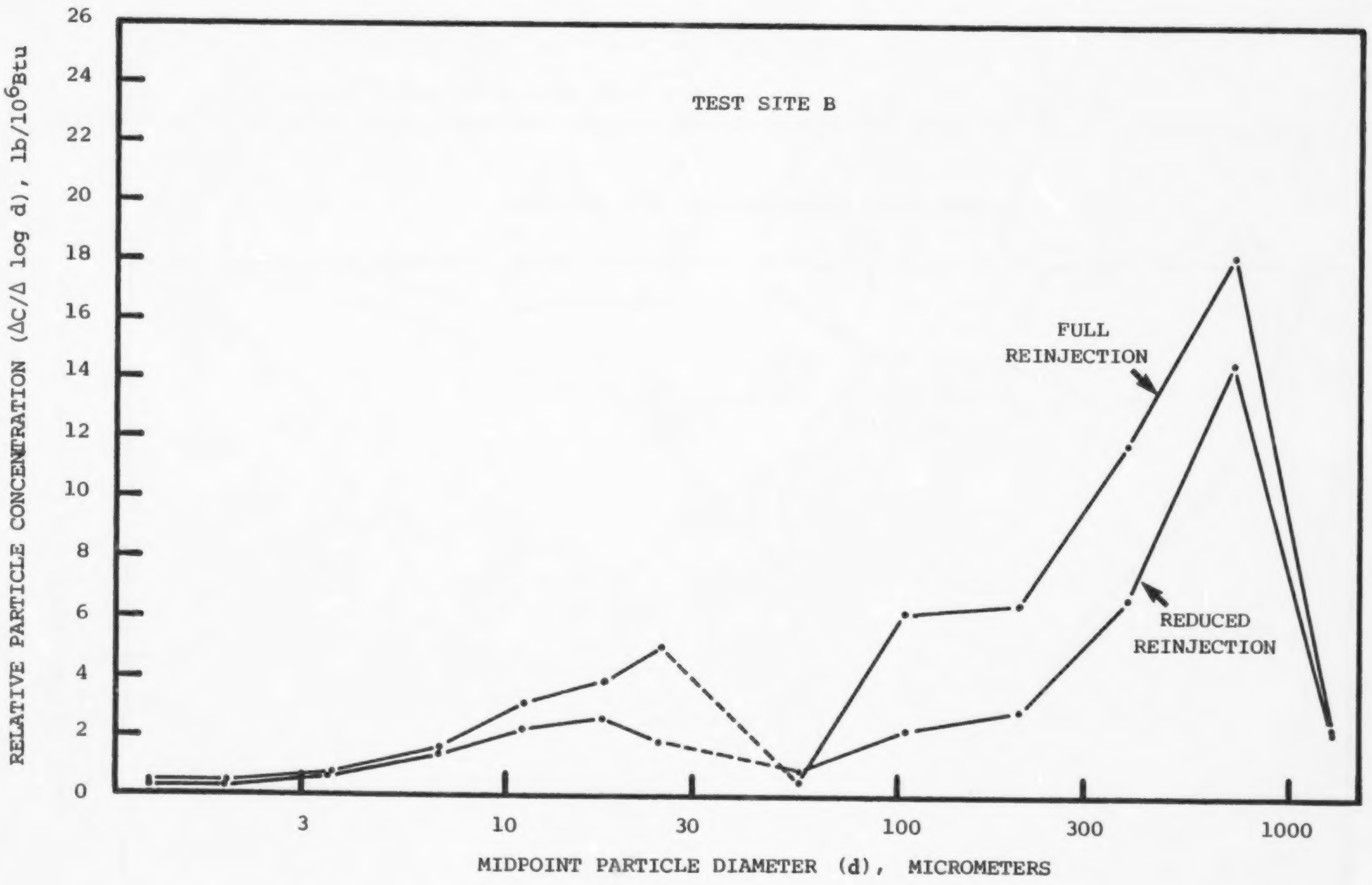

Figure 3-66. Particle Size Concentrations for Boiler Outlet Particulates under Normal and Reduced Flyash Reinjection Conditions - Test Site B.

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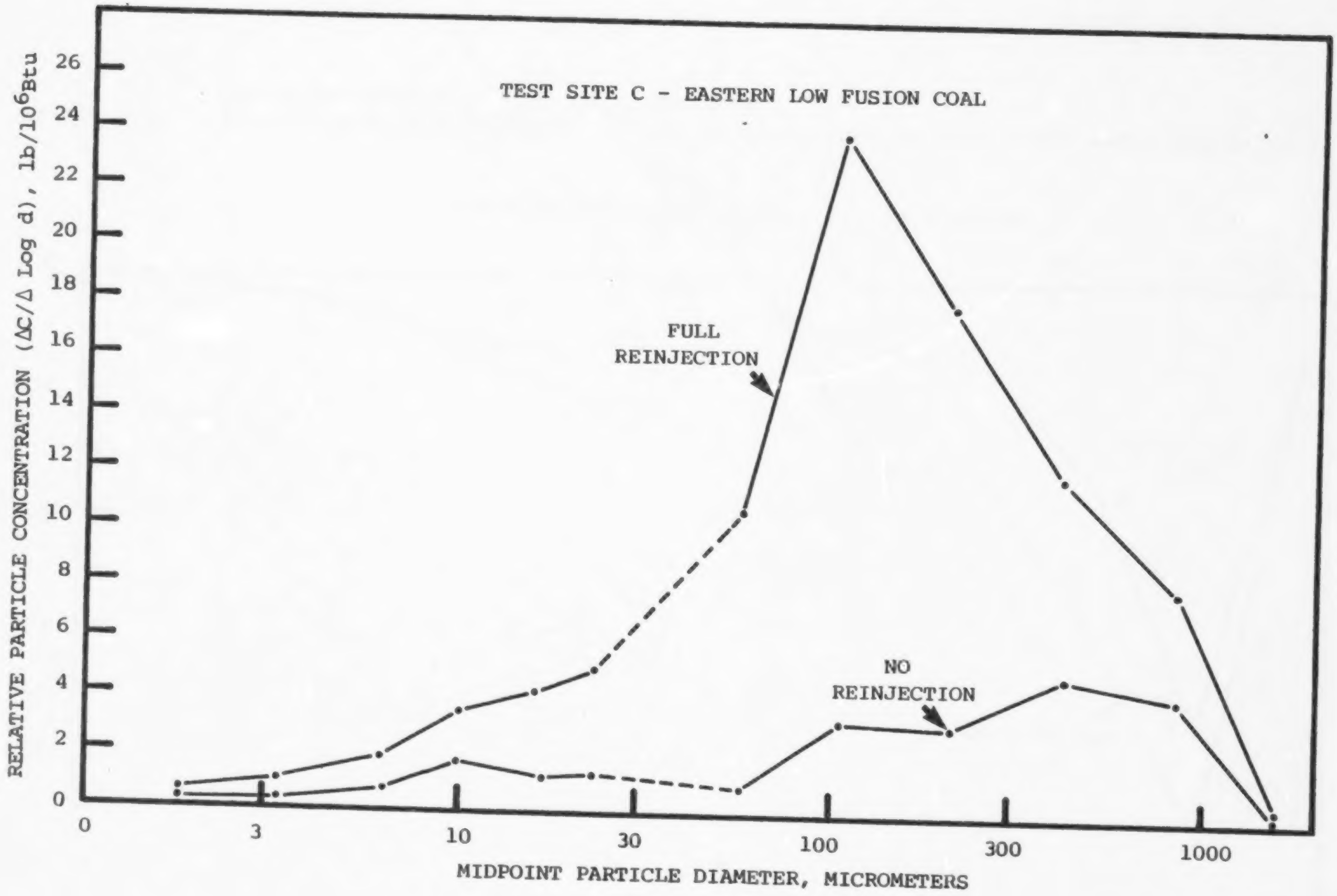

Figure 3-67. Particle Size Concentrations for Boiler Outlet Particulates under Full and Reduced Flyash Reinjection Conditions - Eastern Low Fusion Coal - Test Site C.

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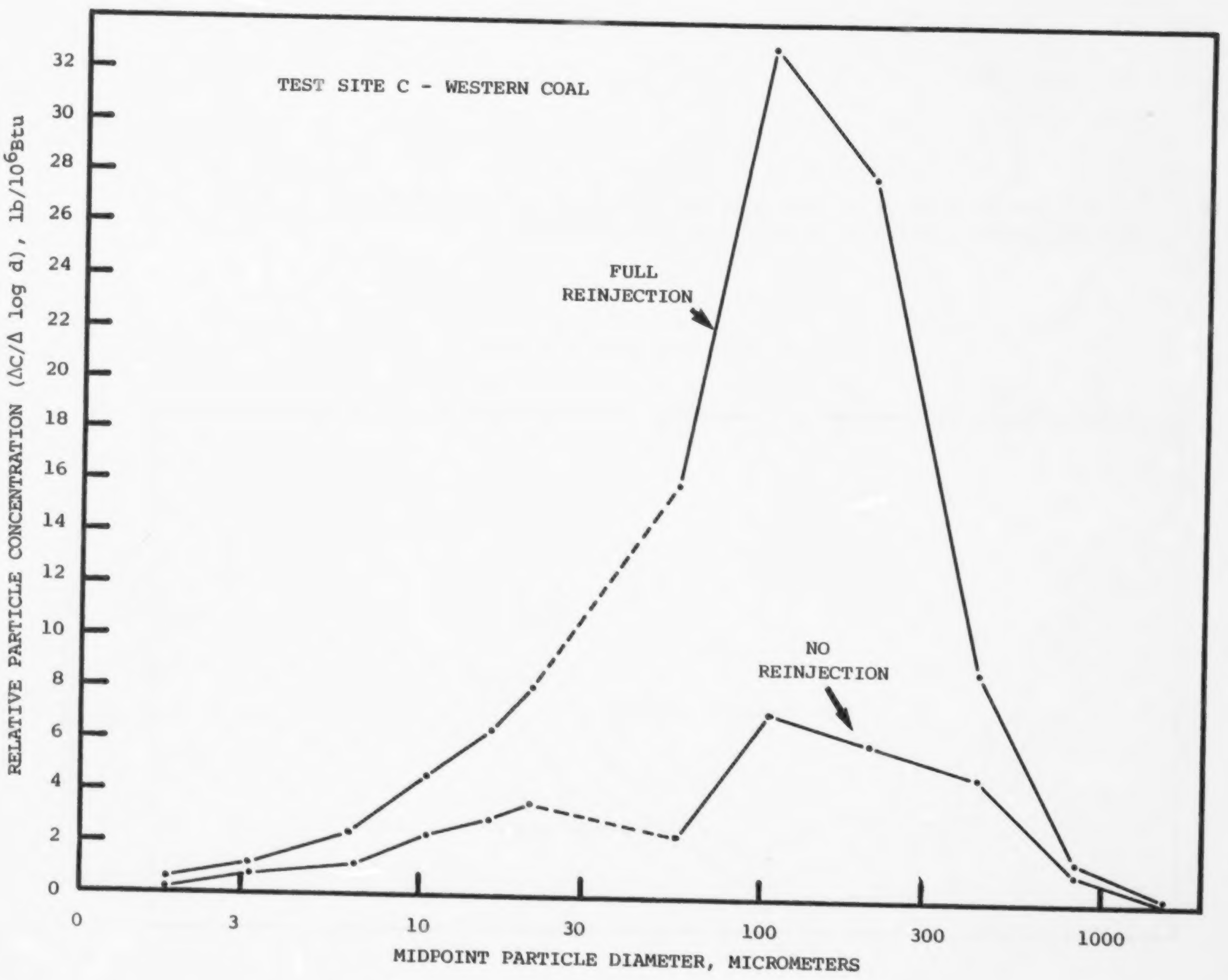

Figure 3-68. Particle Size Concentrations for Boiler Outlet Particulates under Full and Reduced Flyash Reinjection Conditions - Western Coal - Test Site C.

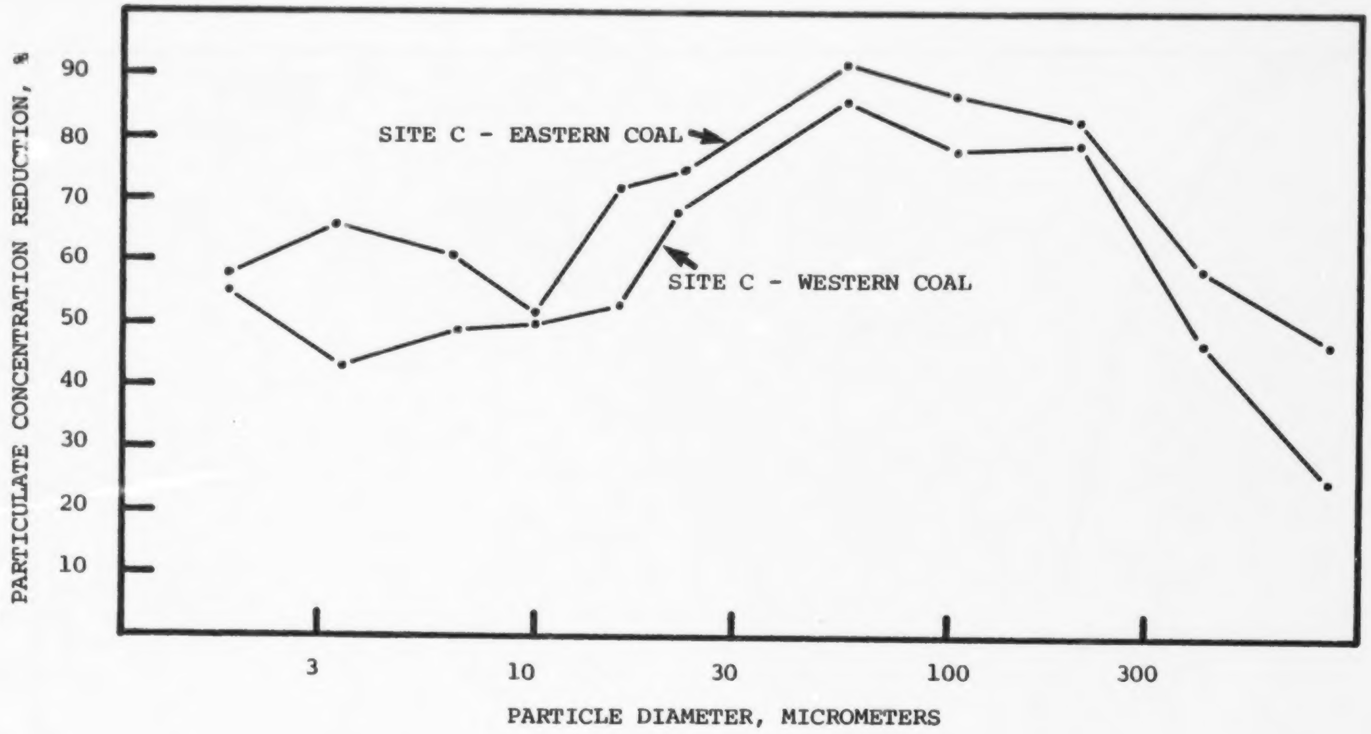

Figure 3-69. Particulate Concentration Reduction as a Function of Particle Diameter for the Change in Flyash Reinjection Configuration from Full to No Reinjection - Test Site C.

3.7.7 Reinjection From an Economizer Hopper - Test Site F

Reinjection tests were also conducted at Test Site F. Site F does not reinject flyash from the mechanical dust collector. However, it does reinject flyash pneumatically and continuously from the economizer hopper and from the boiler hopper. During one test, the flyash collecting in the economizer hopper was diverted to barrels rather than reinjected. This resulted in a 5-27% drop (depending on which test you compare it to) in particulate mass loading at the economizer outlet when compared to the full reinjection test data. The data also indicate that during this test, ten percent of the flyash entering the economizer was collected in the economizer hopper.

The Site F particulate loading results are presented in Table 3-37 for the case of reduced reinjection and for four comparable full reinjection tests. As with the tests on Sites B and C, the Site F particle distribution was shifted towards smaller particles by the reduced reinjection. These data are presented in Figure 3-70.

TABLE 3-37

PARTICULATE LOADING VS FLYASH REINJECTION
TEST SITE F

Flyash Reinj.	Test Conditions			Economizer Outlet Particulate Loading $lbs/10^6Btu$	% by Which Reduced Reinjection Particulate Loading is Lower
	% Load	% O_2	OFA		
NO	100	6.3	High	5.24	--
YES	99	6.7	Norm	5.51	5%
YES	99	7.8	Norm	5.93	12%
YES	99	5.5	High	6.14	15%
YES	102	5.0	High	7.18	27%

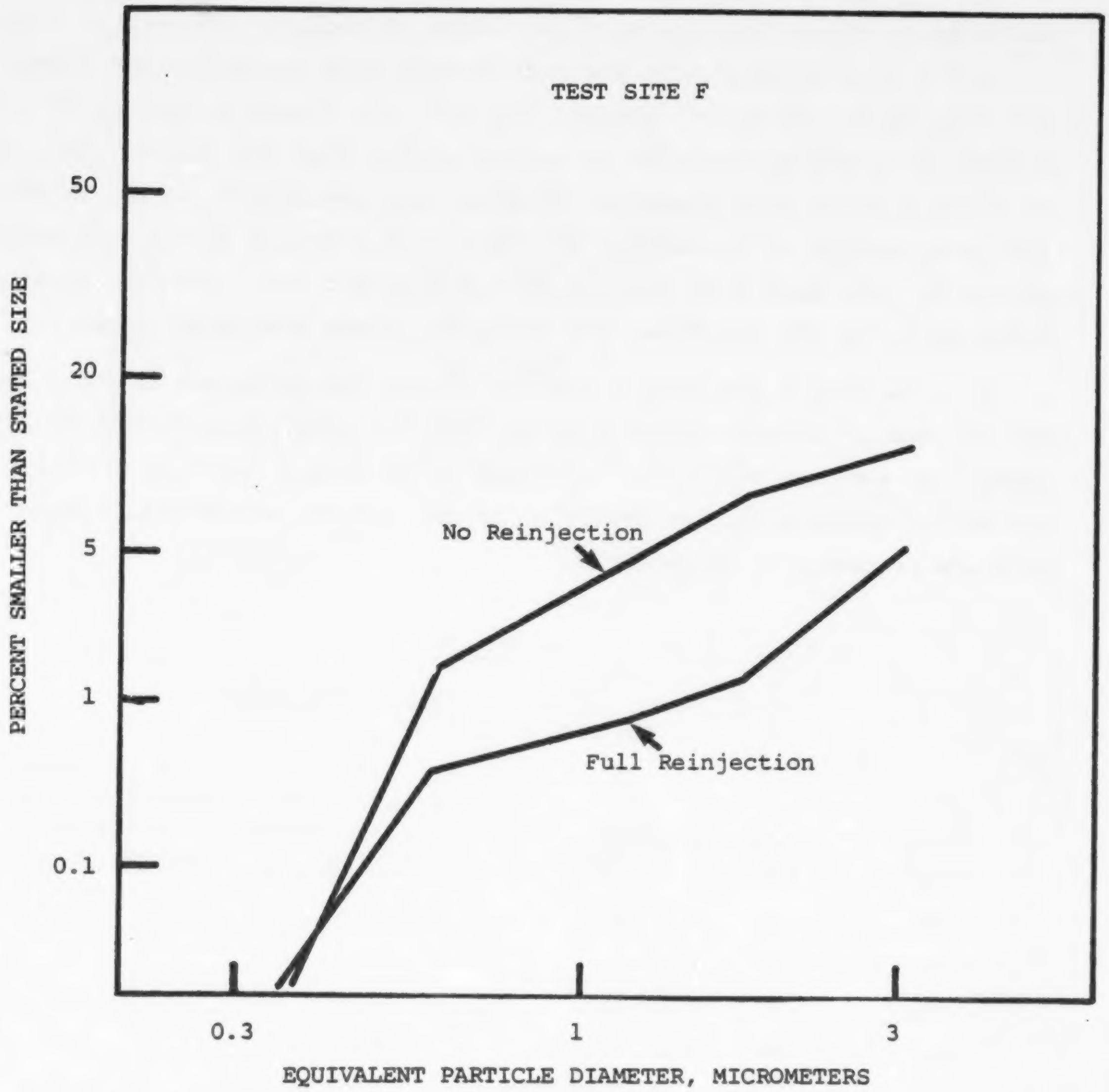

Figure 3-70. Particle Size Distribution at the Economizer Outlet for Full and Reduced Reinjection From the Economizer Hopper at Site F.

3.7.8 Stratification and Density of Ash in Collection Hoppers

In the course of performing the reduced reinjection tests at Sites C and F, the flyash collection rate was measured from each downcomer. These data are of interest because they show how evenly the ash is distributed to the various reinjection lines.

At Site C, the ash collected in the boiler hopper of this single pass boiler was heavier at the sides than in the center of the hopper. These data are shown in Table 3-38 for two tests. The bulk density of the Eastern coal ash was determined to be 16.6 lb/ft^3 at this location.

TABLE 3-38

BOILER HOPPER ASH DISTRIBUTION AT SITE C

	← Right				Left →		
	1	2	3	4	5	6	7
Eastern Coal Ash, lb/hr	60	54	59	41	46	69	106
Western Coal Ash, lb/hr	37	43	48	14	34	71	79

The ash collected from the three economizer hoppers at Site F showed considerable stratification. Most of the ash was collected in the center hopper. The results for a two-hour, ten-minute period are shown in Table 3-39.

TABLE 3-39

ECONOMIZER ASH DISTRIBUTION AT SITE F

	Left Hopper	Center Hopper	Right Hopper
Flyash Collection Rate	12.9 lb/hr	36.5 lb/hr	4.4 lb/hr

3.8 PARTICLE SIZE DISTRIBUTION OF FLYASH

Particle size distribution of the flyash was determined using several different methods. These include a Brink cascade impactor, a Bahco classifier, the cyclone train from the Source Assessment Sampling System (SASS), a Coulter Counter, and sieve analysis. These methods differ in the size range of particles each classifies, as well as in the method of classification. In addition, the results obtained from each method differ from one another. Therefore, it is necessary to present the results of each method separately and to discuss the peculiarities of each.

3.8.1 Brink Cascade Impactor Test Results

The primary method employed for determining particle size distribution of the flyash was the Brink cascade impactor. The Brink was selected at the beginning of this program after consultation with both the Testing Techniques Group of the U. S. Environmental Protection Agency, and Southern Research Institute who have considerable experience with cascade impactors. The Brink was selected over other cascade impactors because its comparatively low sample rate would allow the largest sampling period under the high mass loading conditions at the boiler outlets of spreader stokers. A long sampling period was desired so as to provide a reasonable averaging of transient conditions.

The Brink cascade impactor and the manner in which it was used had its drawbacks. Because of its low sample rate, it was necessary to use small nozzles of 2.0 mm diameter in order to maintain isokinetic sampling rates. At the boiler outlet of spreader stokers, the flyash particles are as large as 2.0 mm, the same size as the sampling nozzle. As a result, tests in which EPA Method 5 particulate loading were run simultaneously with the Brink revealed that the Brink was collecting only 26% to 87% of the flyash particles. This had the effect of biasing the particle size distribution data in favor of more smaller particles. Table 3-40 compares the Brink and the EPA Method 5 data.

The Brink cascade impactor data has two more drawbacks. First, because the Brink was used as a single point sampler, stratification of the flyash particles within the duct could lead to error. Multiple point sampling with a cascade impactor is only possible by compromising on isokinetics. Secondly,

TABLE 3-40

A COMPARISON OF BRINK AND EPA METHOD 5 DUST LOADING DATA

Site	Test	Brink Loading gr/DSCF	EPA Method 5 Loading gr/DSCF	Brink as % of Method 5
E	11	.563	2.160	26%
E	14	1.872	3.824	49%
F	23	1.463	2.748	53%
F	24	1.331	3.932	34%
F	29	2.036	3.243	63%
G	5	2.205	3.102	71%
G	17	2.224	2.550	87%

the size range of particles classified by this 5 stage impactor is 0.3 micrometers to 3.0 micrometers. This is too small to be useful for predicting dust collector efficiencies.

Data reduction was accomplished with the aid of a computer and followed the procedures outlined in EPA publication 600/2-77-004, Procedures for Cascade Impactor Calibration and Operation in Process Streams, January, 1977.

Test Data. The Brink data are plotted on the traditional log-probability scale in Figures 3-71 and 3-72. Examining the data statistically yields the average size distribution given in Table 3-41.

TABLE 3-41

AVERAGE BRINK CASCADE IMPACTOR DATA FOR SPREADER STOKERS

	Mass Percent Less than Stated Size and Standard Deviation		
	0.3 μm	1.0 μm	3.0 μm
Boiler Outlet	0.8±1.2	2.2±1.4	6.6±3.4
DC Outlet	2.1±2.0	9.0±4.4	37.6±13.4

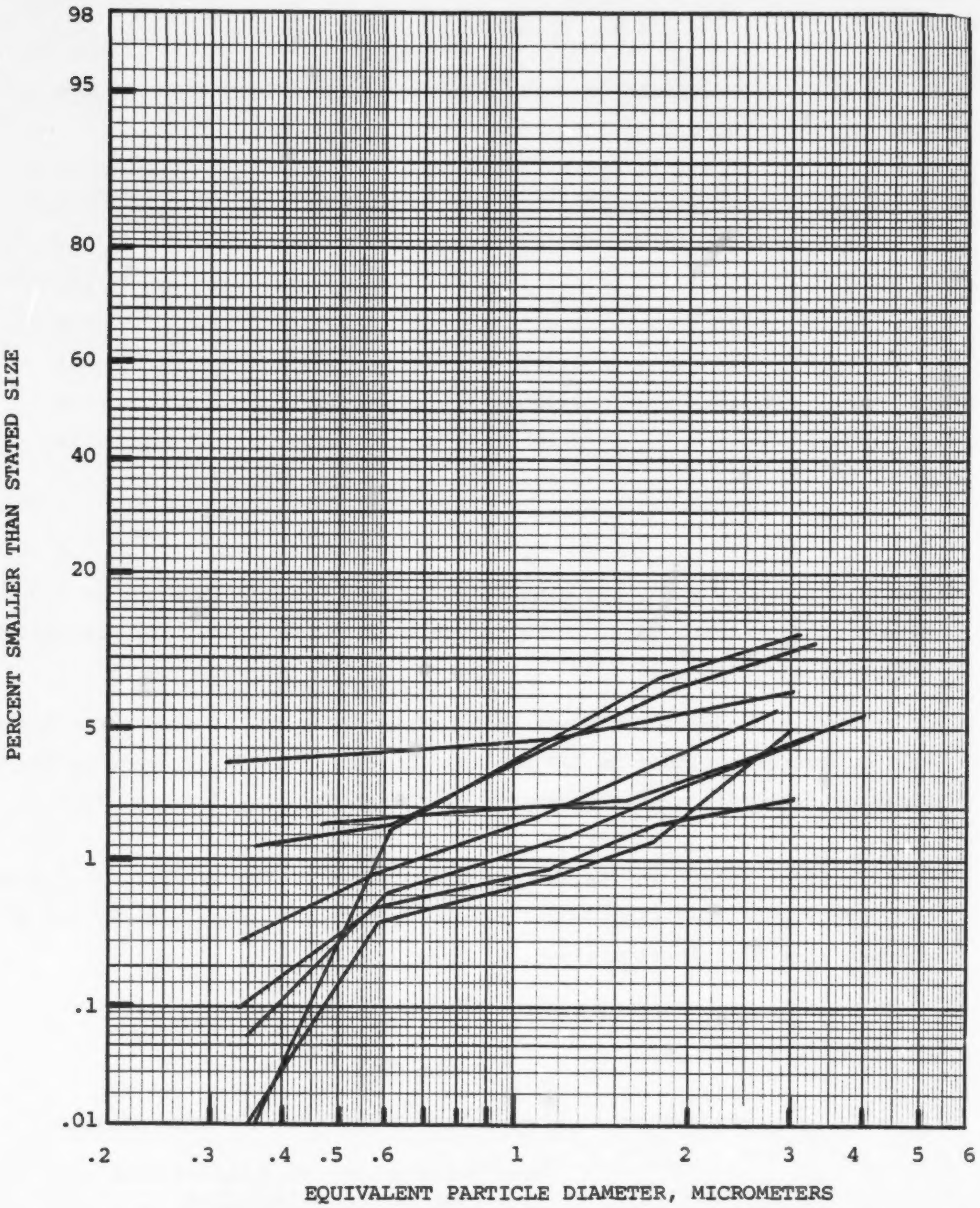

Figure 3-71. Particle Size Distribution at the Boiler Outlet as Determined by Cascade Impactor. Data are from Full Load Tests on Spreader Stokers, Sites E, F and G.

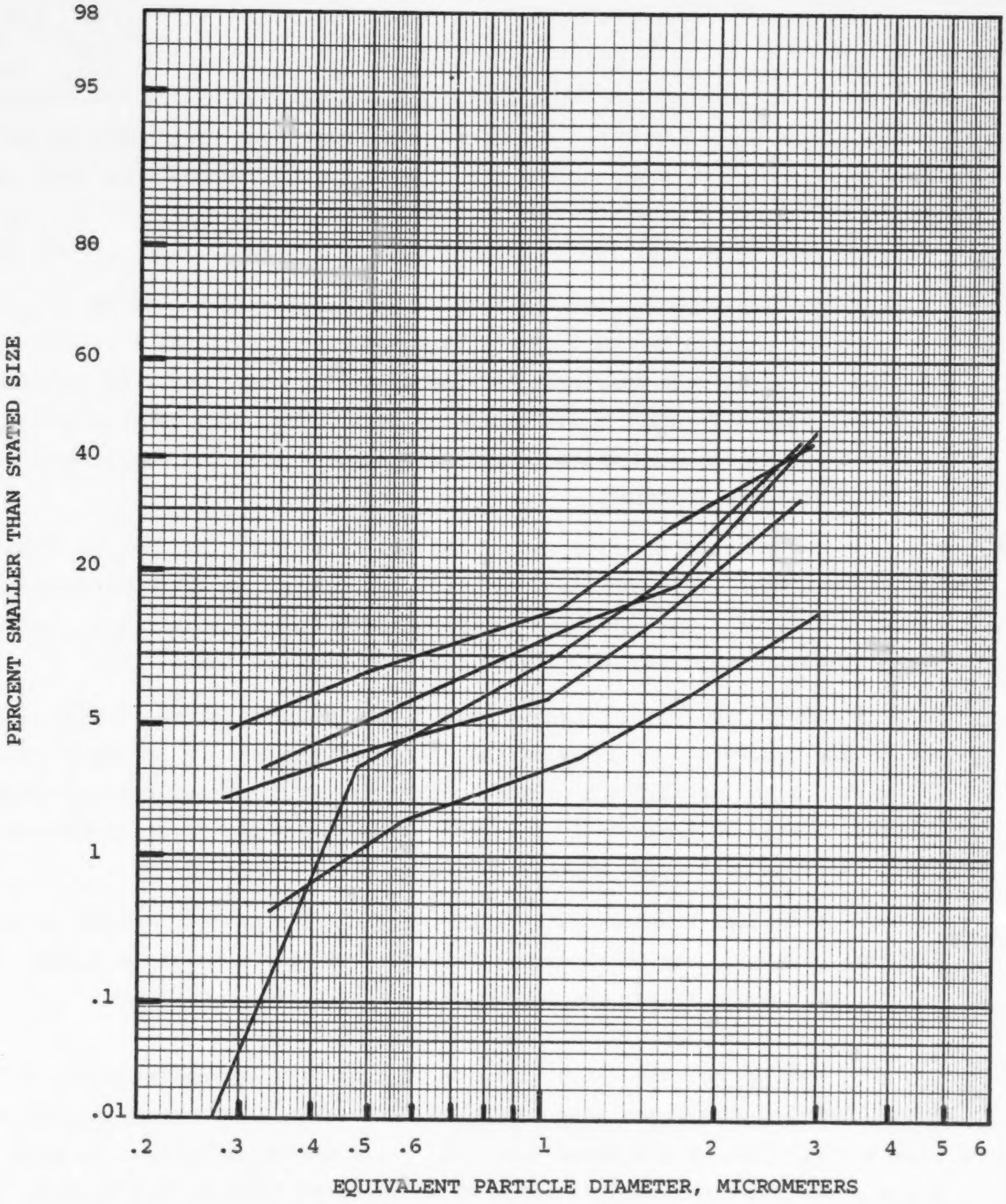

Figure 3-72. Particle Size Distribution at the Mechanical Collector Outlet as Determined by Cascade Impactor. Data are from Full Load Tests on Spreader Stokers, Sites B and C.

3.8.2 Bahco Classifier Test Results

Another method employed for determining particle size distribution of the flyash was the Bahco classifier. This method has been used in the power industry for many more years than the relatively new cascade impactors, and has received wide acceptance. It is described in ASME Power Test Code 28. This method involves transporting a collected ash sample to a laboratory for analysis.

In this program, the ash samples were collected in the cyclone which is a part of the EPA Method 5 particulate sampling train. As a result, the samples collected were spacially representative in that they were isokinetically collected from a 24-point traverse of the duct. The range of size classification is 1.5 to 25 micrometers which is more appropriate than the range obtained from the Brink cascade impactor.

The Bahco classifier method has its drawbacks. As with all cyclone collected samples, the smallest particles are not collected as efficiently as the larger particles. The estimated cut point of the cyclone used was 7 micrometers which is within the size range being classified by the Bahco.

The collection efficiency of the cyclone used in these tests was accurately determined by dividing the cyclone catch mass by the total catch mass. The total catch included the cyclone catch, filter catch and acetone rinse. The results, listed in Table 3-42, show that between 1.4 and 12.2% of the sample was lost. Average collection efficiency was 94.5%.

Potential drawbacks to the Bahco classifier method include the possibility that particles may break-up, agglomerate, or absorb moisture during transit, all of which would affect the outcome of the analysis.

Test Data. The Bahco data are plotted on a log-normal scale in Figure 3-73. Bahco analysis was only run on boiler outlet flyash samples. The average size distribution of the Bahco data, and its standard deviation, is given in Table 3-43. As expected, the Bahco data indicates fewer particles below 3 micrometers than does the Brink data. The percentages are 1.8% versus 6.6%, respectively. Because the two methods are believed to be biased in opposite directions, the true size distribution should lie somewhere in between.

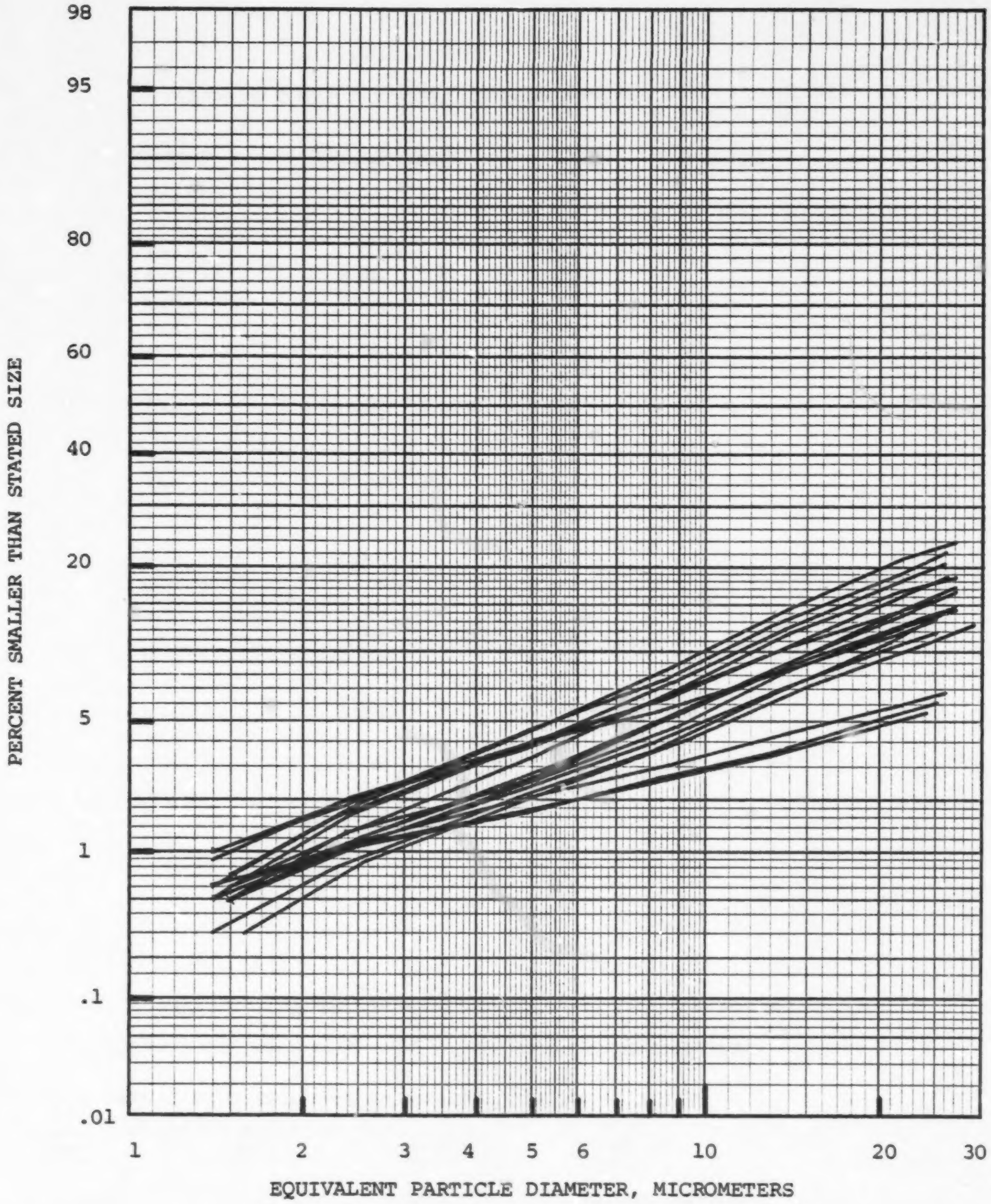

Figure 3-73. Particle Size Distribution at the Boiler Outlet as Determined by Bahco Classifier. Data are from Full Load Tests on Spreader Stokers, Sites A, B, C F and G.

TABLE 3-42

COLLECTION EFFICIENCY OF BAHCO SAMPLES

Site	Test	% Collected	% Lost
A	30	97.1	2.9
B	4	97.0	3.0
B	23	97.5	2.5
B	24	96.7	3.3
B	25	97.1	2.9
B	26	95.1	4.9
C	9	96.6	3.4
C	10	92.2	7.8
C	24	98.6	1.4
C	36	96.5	3.5
C	42	98.4	1.6
F	5	96.1	3.9
F	21	91.0	9.0
F	23	94.0	6.0
F	24	93.8	6.2
F	29	93.9	6.1
G	4	89.1	10.9
G	5	93.4	6.6
G	8	87.8	12.2
G	17	91.9	8.1
G	18	91.2	8.8

TABLE 3-43

AVERAGE BAHCO CLASSIFIER DATA FOR SPREADER STOKERS

	Mass Percent Less than Stated Size and Standard Deviation		
	3 μm	10 μm	20 μm
Boiler Outlet	1.8±0.5	6.2±2.1	12.1±4.4

3.8.3 SASS Cylcone Test Results

A third method employed to measure particle size distributions was the cyclone train from the Source Assessment Sampling System (SASS). This data is a byproduct of the SASS sampling for trace elements and organic species. The method involved drawing a sample isokinetically from a single point in the duct and passing it through three calibrated cyclones at a controlled temperature and flow rate.

Like the Brink cascade impactor it has the advantage of sizing the entire sample without losses. It has an advantage over the Brink in that it is a high volume sampler using relatively large nozzles of nominally 5/8 inch (1.59 centimeters) diameter. Despite the large nozzles, the sampled dust loadings were an average 23% less than the corresponding EPA Method 5 particulate loadings. A disadvantage of the SASS data is that it was obtained from a single point and may be biased in either direction due to stratification within the duct.

Test Data. The SASS cyclone particle size distribution data are shown in Figures 3-74 and 3-75. It should be noted that the cut points of the calibrated cyclones used for tests at Sites A, B and C were 1, 3 and 10 micrometers. At Sites E, F and G, the cut-points were 1.4, 5.9 and 18.5 micrometers. The average and standard deviation of the boiler outlet data are given in Table 3-44. Since there were only two tests each at the mechanical collector outlet at Site B, and at the electrostatic precipitator outlets of Sites A and B, these data are presented without averaging. The Site A data obtained at the ESP outlet reflects the fact that three of the four precipitator fields were out-of-service during these two tests.

TABLE 3-44

AVERAGE SASS CYCLONE DATA FOR SPREADER STOKERS

	Mass Percent Less than Stated Size and Standard Deviation		
	1.0 μm	3.0 μm	10.0 μm
Boiler Outlet	1.7±1.4	4.9±2.8	15.9±9.0
DC Outlet (Site B)	3.6-13.2	17.3-40.8	41.5-78.0
ESP Outlet (Site A)	19.8-20.8	58.1-62.6	75.5-82.2
ESP Outlet (Site B)	85.2-86.0	85.2-87.0	88.8-93.8

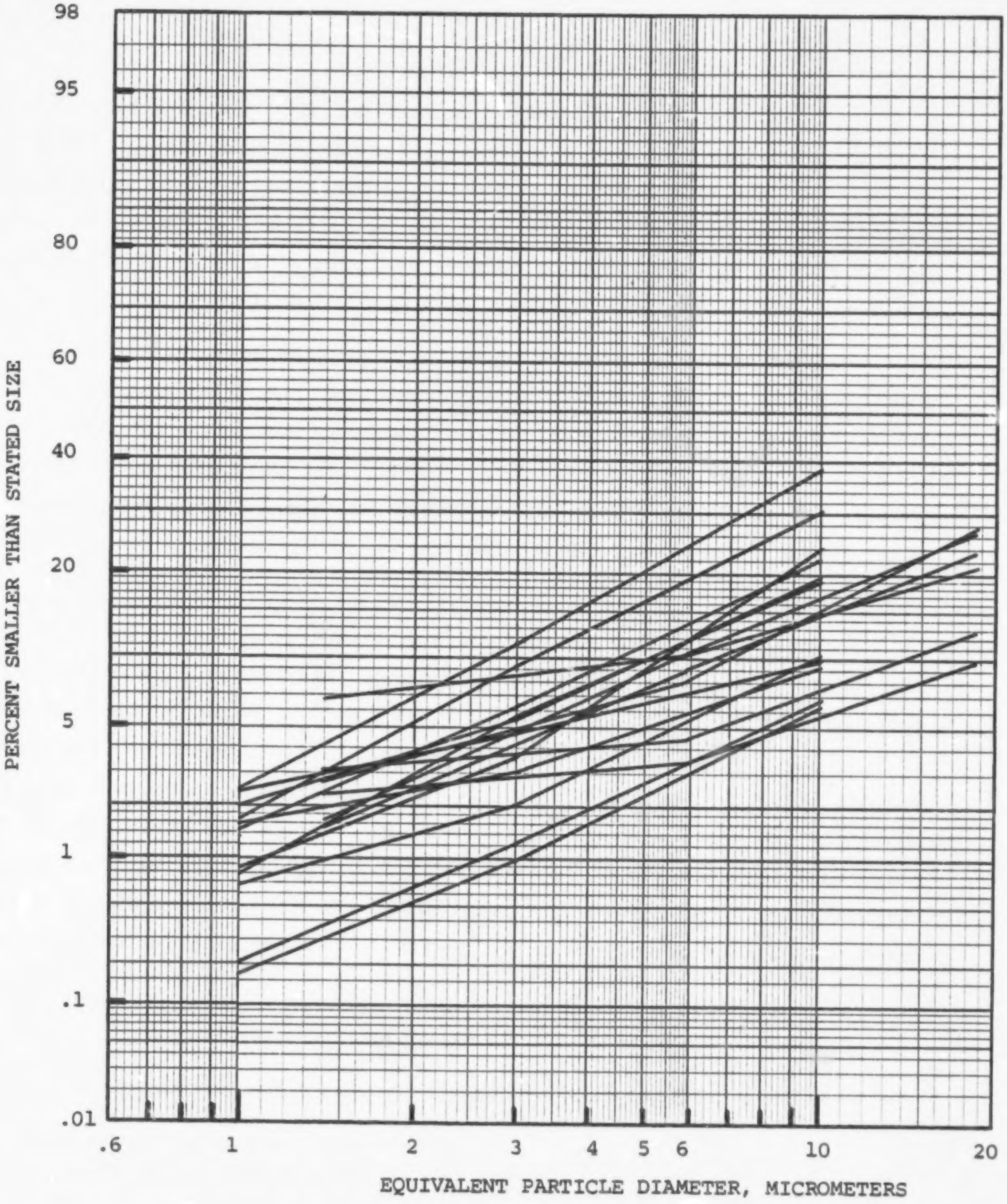

Figure 3-74. Particle Size Distribution at the Boiler Outlet as Determined by SASS Cyclones. Data are from Full Load Tests on Spreader Stokers, Sites A, B, C, E, F and G.

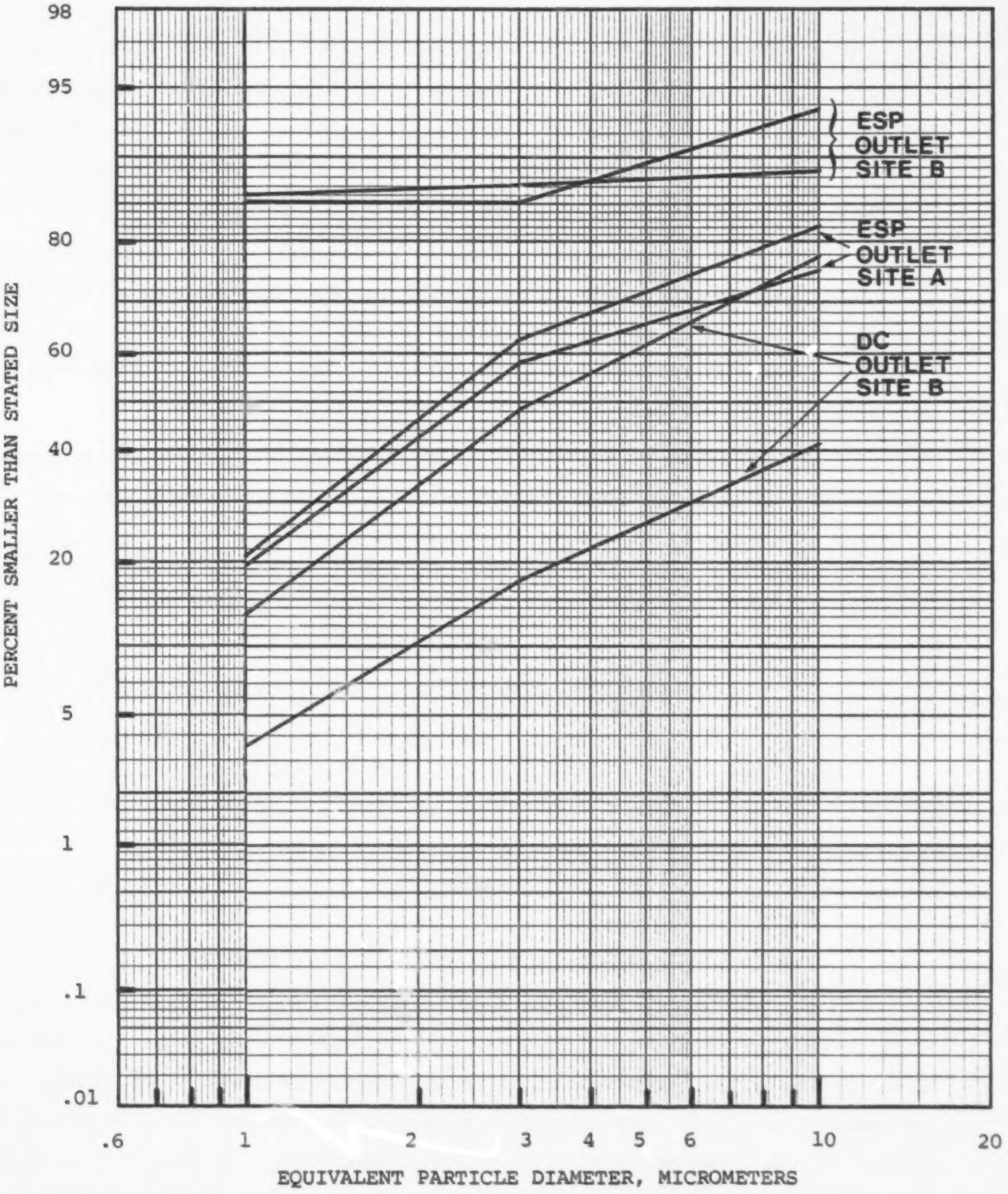

Figure 3-75. Particle Size Distribution at the Mechanical Collector Outlet and the Electrostatic Precipitator Outlet as Determined by SASS Cyclones. Data are from Tests on Spreader Stokers, Sites A and B, at Loads Ranging from 75 to 89% of Design Boiler Capacity.

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3.8.4 Coulter Counter and Sieve Analysis Test Results

Sieve analysis was performed on 21 flyash samples collected at the boiler outlets of five spreader stokers. The samples were collected with the cyclone in the EPA Method 5 train. Seven sieve sizes were used, ranging from ten mesh (1650 micrometers) to 325 mesh (44 micrometers).

The sieve data are plotted on a log-probability scale in Figure 3-76. To simplify the presentation, this plot shows only the average of the full load test data for each of the five spreader stokers. In addition to the seive analysis, one sample was run through a coulter counter. The results of this test are represented by the dashed line.

The sieve data show that particles at the boiler outlets of spreader stokers are as large as 1000 to 2000 micrometers in diameter. The average and standard deviation of this data is presented in Table 3-45.

TABLE 3-45

AVERAGE SIEVE ANALYSIS DATA FOR SPREADER STOKERS

	Mass Percent Less than Stated Size and Standard Deviation			
	44 μm	100 μm	300 μm	1000 μm
Boiler Outlet	13.4±7.1	24.7±12.7	54.1±18.8	97.9±1.5

3.8.5 Combustibles vs Particle Size Distribution

One ash sample from the dust collector hopper at Test Site A was sieved into three size ranges and baked for combustible determination. The results, given in Table 3-46, show that the larger particles contain the highest combustible content. This is in keeping with the results of combustible determinations on the flyash at the inlet and outlet of the dust collector. At the collector inlet, the flyash averaged 58.4% combustibles. At the collector outlet after the largest particles had been removed, the flyash averaged only 30.3% combustibles.

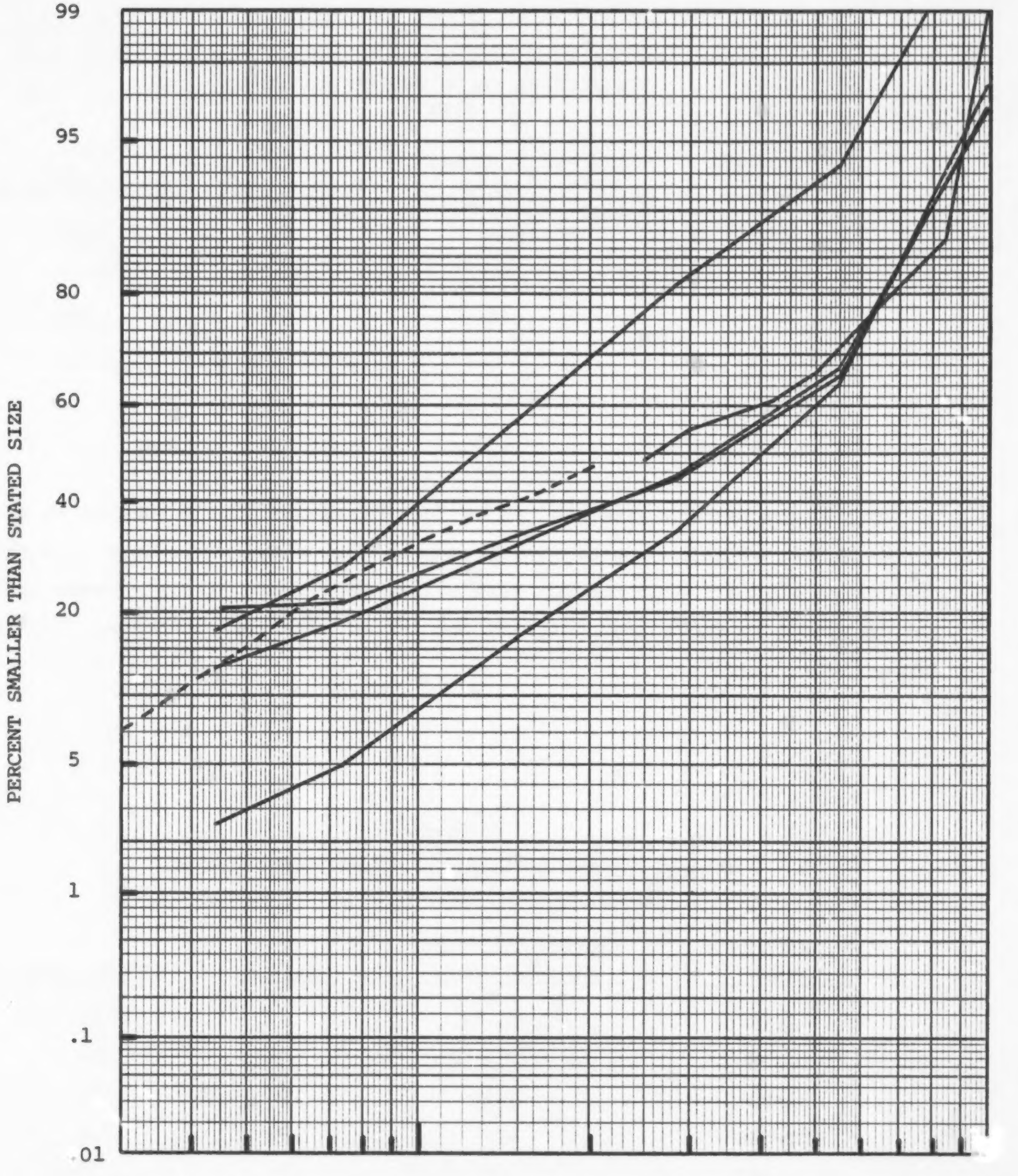

Figure 3-76. Sieve Analysis of Flyash Collected at the Boiler Outlets of Five Spreader Stokers. Each Line Represents the Average of the Full Load Data for Each Site. Dashed Line Represents Results of Coulter Counter Analysis of a Single Ash Sample.

TABLE 3-46

COMBUSTIBLES VS DC HOPPER ASH SIZING
SITE A

Tyler Screen Mesh	Average Diameter Micrometers	Mass, %	Combustibles, %
-10+20	1,242	4.3	72.6
-20+100	490	34.4	61.3
-100	74	61.3	5.0
		Weighted Average	27.3

A similar analysis was run on four flyash samples collected at the boiler outlet at Test Site B. These samples were sieved into five size ranges. The analysis of all four samples were nearly identical. Their average analysis are presented in Table 3-47. Again, the larger particles contained the higher combustible fractions.

TABLE 3-47

COMBUSTIBLES VS BOILER OUTLET FLYASH SIZING
SITE B

Tyler Screen Mesh	Average Diameter Micrometers	Mass, %	Combustibles, %
-8+16	1,326	6	91
-16+35	713	29	84
-35+80	303	19	64
-80+200	128	19	34
-200	38	27	17
		Weighted Average	53%

3.8.6 Dust Collector Efficiency vs Particle Size Distribution

There are a number of factors which influence dust collector efficiency besides particle size distribution. These include design, state of repair, inlet dust loading and pressure drop across the cyclone tubes.

A comparison is made in Figure 3-77 between collector efficiency and percentage of particles smaller than 20 micrometers. To minimize the other variables, only full load data are shown, and the test sites are identified. The data are further restricted to Bahco classifier tests of ash samples which were accompanied by a simultaneous dust collector efficiency test.

In Figure 3-77, the data from Sites B, C and G behaved very similar. There is a slight decrease in efficiency as the percentage of particles larger than 20 micrometers increased. Test Site F had much lower dust collector efficiencies than the others despite the coarseness of the particles entering the collector. This could be the result of the collector's design or state of repair, or it could be measurement error. There is insufficient information available to resolve this difference.

Finally, it is worth noting that dust collector efficiency did not drop off significantly as load decreased on spreader stokers except when it was reduced to 20% of capacity as it was on Test Site G. Figure 3-78 illustrates the dust collector efficiency data for four spreader stokers. Data from Site E are not included in this figure. The collector efficiency at Site E deteriorated during the test program from 84-96% in early tests to 41-68% in later tests as the result of an undiagnosed problem. Test Site A is also omitted from Figure 3-78 because simultaneous dust loadings were not determined across its collector.

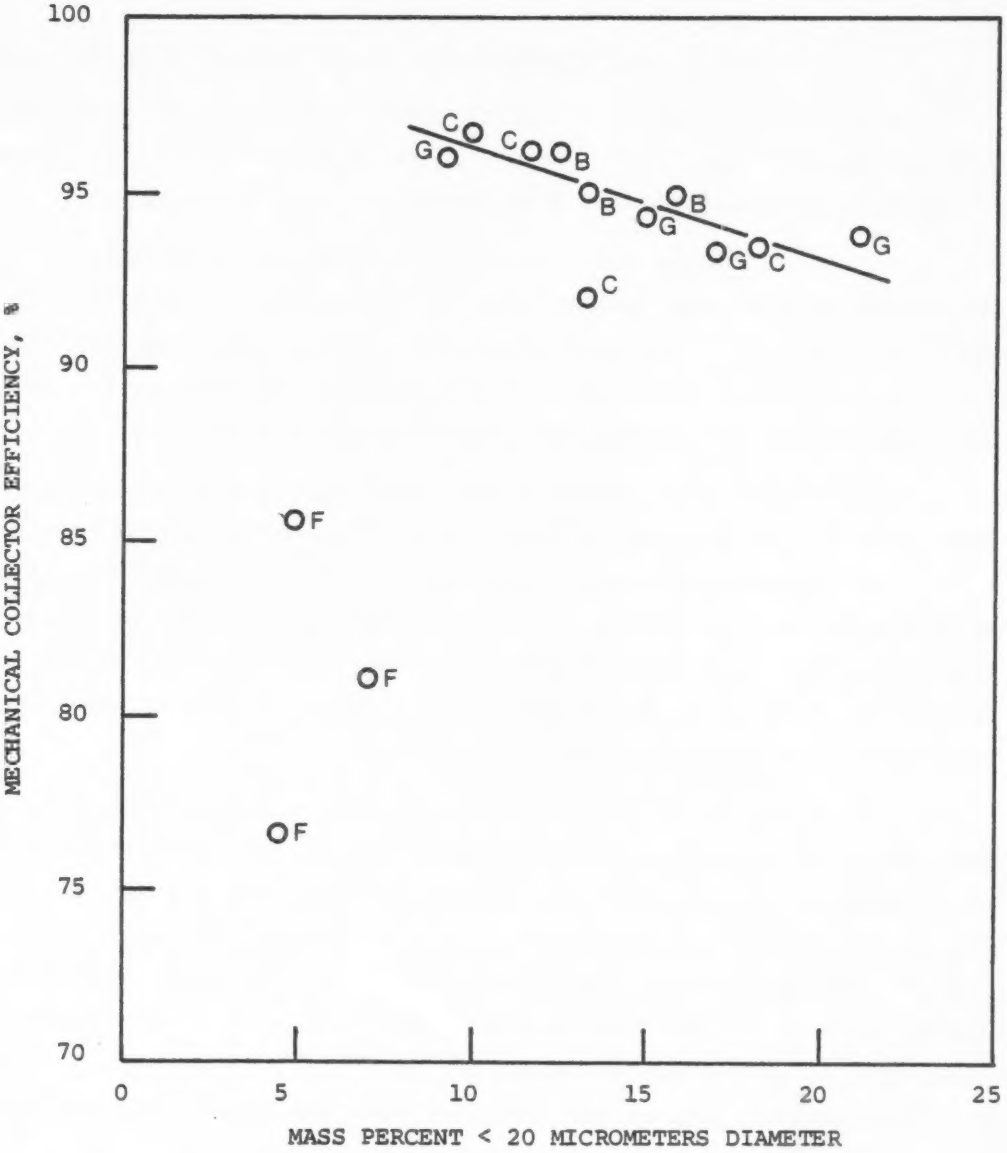

Figure 3-77. Relationship Between Percentage of Particles Smaller than 20 Micrometers, and Dust Collector Efficiency for Spreader Stokers. Only Bahco Data from Full Load Tests are Indicated. Line Represents an Observed Trend.

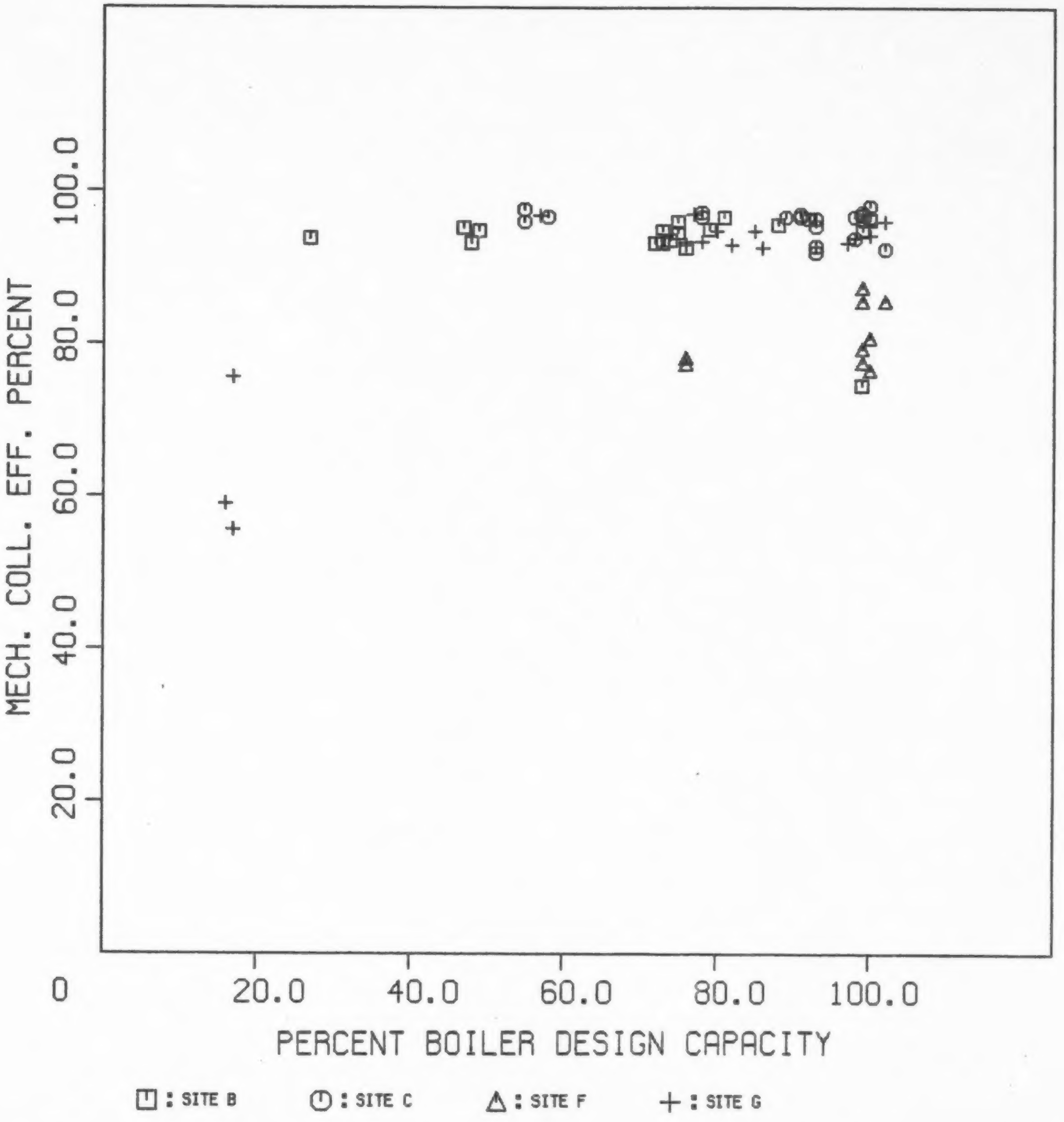

FIG. 3-78
MECH. COLL. EFF. VS. PERCENT DESIGN CAPACITY

4.0 MASS FIRED OVERFEED STOKERS

4.1 DESCRIPTION OF UNITS TESTED

Mass fired overfeed stokers differ from spreader stokers in the manner by which fuel is fed onto the grate. In this type of stoker, a layer of coal is continuously layed down on one end of the grate. The motion of the grate conveys this coal continuously through the furnace where it is consumed. Ash is continuously discharged at the opposite end of the grate. Mass fired overfeed stokers have burning characteristics which are uniquely different from spreader stokers and underfeed stokers and are therefore discussed as a separate group in this report.

The mass fired overfeed stokers tested for this program represent the most common designs specified today. All seven stokers in this group are balanced draft units having both forced draft and induced draft fans. All are equipped with overfire air on the front wall, and none have any form of flyash reinjection. Two of the stokers utilize a water cooled vibrating grate to transport the coal and ash through the furnace. The other five utilize continuous traveling or chain grates. Two of the stokers were built in 1977, while the other five were built between 1959 and 1969. All seven mass fired stokers represent state-of-the-art designs, since stoker designs have changed very little over the past twenty years.

TABLE 4-1

DESCRIPTION OF MASS FIRED OVERFEED STOKERS TESTED

Site	Year Built	Steaming Capacity lb/hr	Grate Type	Boiler Passes	Backend Equipment by Order of Occurrence
D	1964	90,000	Vibrating	Multiple	ECON, DC
H	1959	45,000	Traveling	Multiple	None
I	1960	70,000	Traveling	Multiple	None
J	1977	70,000	Chain	Multiple	ECON, DC
K	1977	50,000	Traveling	Multiple	ECON, DC
L2	1960	30,000	Vibrating	Multiple	DC
L4	1969	27,000	Chain	Multiple	DC

The following pages present equipment data and general arrangement drawings for each of the seven mass fired overfeed stokers tested. Throughout this report the units will be referred to by the letter designation assigned in this section.

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TABLE 4-2

EQUIPMENT DATA
TEST SITE: D

BOILER:

Year Built	1964
Configuration	Multiple Pass
Rated Steaming Capacity	90,000 lb/hr
Design Pressure	700 psig
Actual Operating Pressure	200 psig
Feedwater Temperature	250°F
Steam Temperature	Saturated
Operating Air Temperature	Ambient

STOKER:

Classification	Mass Fired Water Cooled Vibrating Grate
Effective Length	16.5 Ft
Width	15.5 Ft
Effective Grate Area	256.3 Ft^2

HEATING SURFACES:

Furnace Volume	3,520 Ft^3
Water Wall	737 Ft^2
Boiler	7,706 Ft^2
Superheater	None
Economizer	4,275 Ft^2
Air Heater	None

HEAT RATES AT RATED CAPACITY:

Input to Furnace	103,000,000 Btu/hr
Grate Width Heat Release	6,630,000 Btu/hr-ft
Grate Heat Release	401,000 Btu/hr-ft^2
Furnace Liberation	29,300 Btu/hr-ft^3

OVERFIRE AIR:

Location	Front Upper	Front Lower
Number of Jets x Pipe Size	16x1¼"	16x1¼"
Elevation Above Grate	3.4 Ft	1.4 Ft
Inclination below Horizontal	30°	10°

EMISSION CONTROL EQUIPMENT:	Mechanical Collector

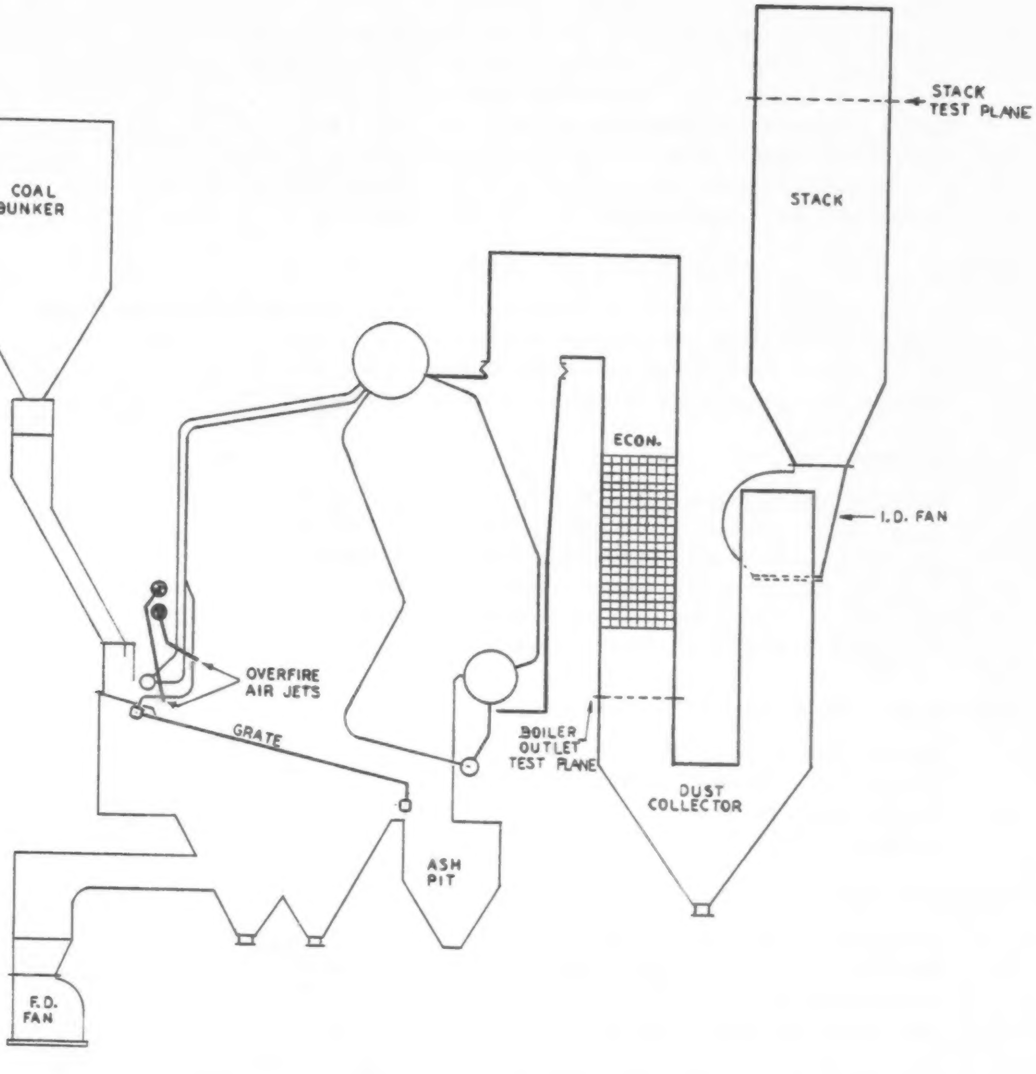
STACK TEST PLANE
STACK
COAL BUNKER
ECON.
I.D. FAN
OVERFIRE AIR JETS
GRATE
BOILER OUTLET TEST PLANE
DUST COLLECTOR
ASH PIT
F.D. FAN

Figure 4-1. • Test Site D General Arrangement Drawing

TABLE 4-3

EQUIPMENT DATA
TEST SITE: H

BOILER:

Year Built	1959
Configuration	Multiple Pass
Rated Steaming Capacity	45,000 lb/hr
Design Pressure	200 psig
Actual Operating Pressure	140 psig
Feedwater Temperature	220°F
Steam Temperature	Saturated
Operating Air Temperature	Ambient

STOKER:

Classification	Mass Fired Traveling Grate
Effective Length	11.0 Ft
Width	13.0 Ft
Effective Grate Area	140.3 Ft^2

HEATING SURFACES:

Furnace Volume	1,850 Ft^3
Water Wall	820 Ft^2
Boiler	5,780 Ft^2
Superheater	None
Economizer	None
Air Heater	None

HEAT RATES AT RATED CAPACITY:

Input to Furnace	59,600,000 Btu/hr
Grate Width Heat Release	4,580,000 Btu/hr-ft
Grate Heat Release	425,000 Btu/hr-ft^2
Furnace Liberation	32,300 Btu/hr-ft^3

OVERFIRE AIR:

Location	Front Wall
Number of Jets x Pipe Size	10x2½"
Elevation Above Grate	4.2 Ft
Inclination below Horizontal	45°

EMISSION CONTROL EQUIPMENT:	None

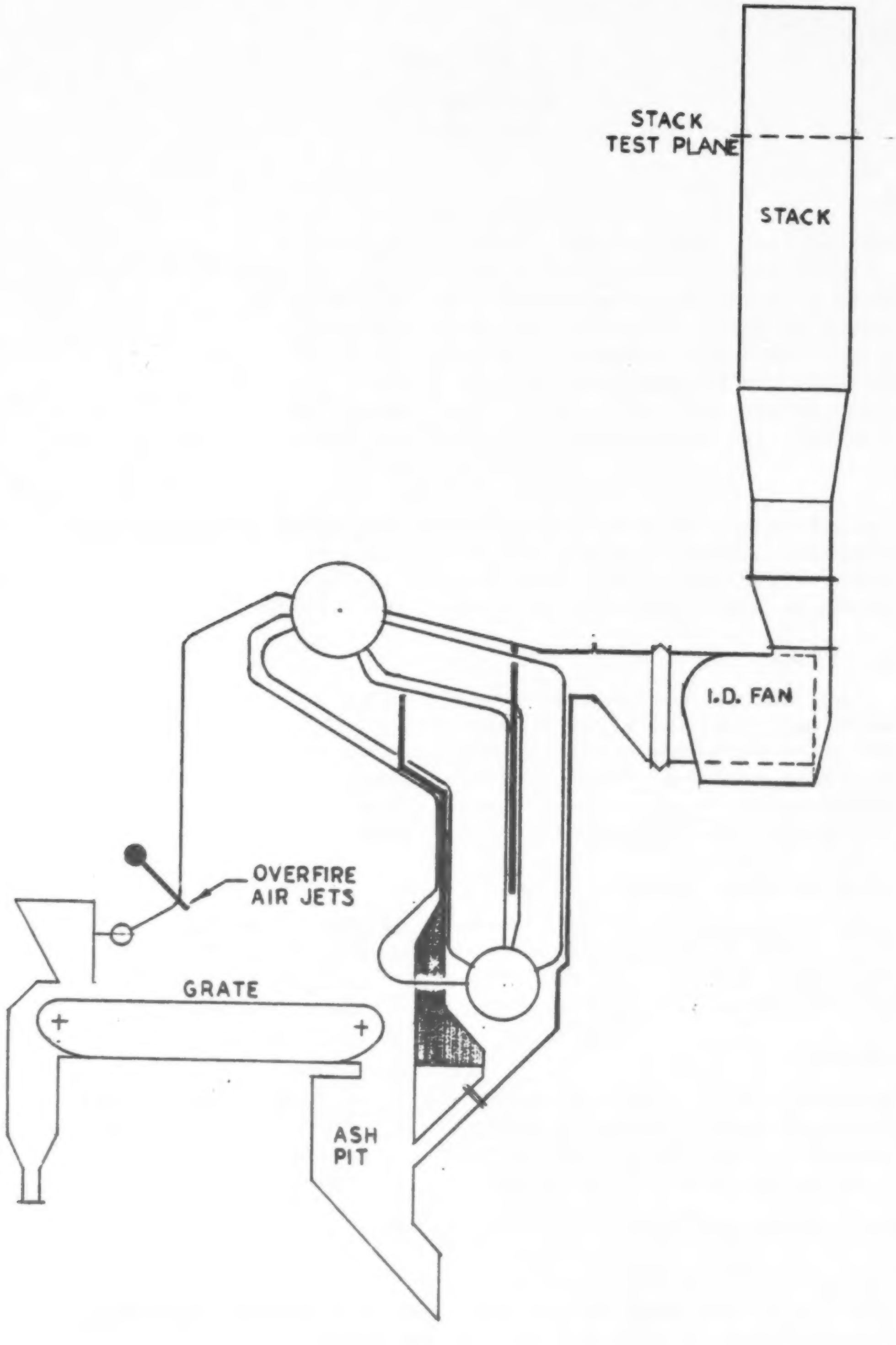
STACK
TEST PLANE
STACK
I.D. FAN
OVERFIRE
AIR JETS
GRATE
ASH
PIT

Figure 4-2. Test Site H General Arrangement Drawing

TABLE 4-4

EQUIPMENT DATA
TEST SITE: I

BOILER:

Year Built	1960
Configuration	Multiple Pass
Rated Steaming Capacity	70,000 lb/hr
Design Pressure	250 psig
Actual Operating Pressure	150 psig
Feedwater Temperature	220°F
Steam Temperature	Saturated
Operating Air Temperature	Ambient

STOKER:

Classification	Mass Fired Traveling Guide
Effective Length	18.0 Ft
Width	14.0 Ft
Effective Grate Area	252.6 Ft^2

HEATING SURFACES:

Furnace Volume	3,900 Ft^3
Water Wall	
Boiler	9,500 Ft^2
Superheater	None
Economizer	None
Air Heater	None

HEAT RATES AT RATED CAPACITY: *

Input to Furnace	95,200,000 Btu/hr
Grate Width Heat Release	6,800,000 Btu/hr-ft
Grate Heat Release	377,000 Btu/hr-ft^2
Furnace Liberation	24,400 Btu/hr-ft^3

OVERFIRE AIR:

Location	Front Upper	Front Lower
Number of Jets x Pipe Size	Unknown	Unknown
Elevation Above Grate	6.8 Ft	4.5 Ft
Inclination below Horizontal	30°	45°

EMISSION CONTROL EQUIPMENT:	None

*Heat rates are based on measured Fuel Flow data at this site, manufacturers design data was not available.

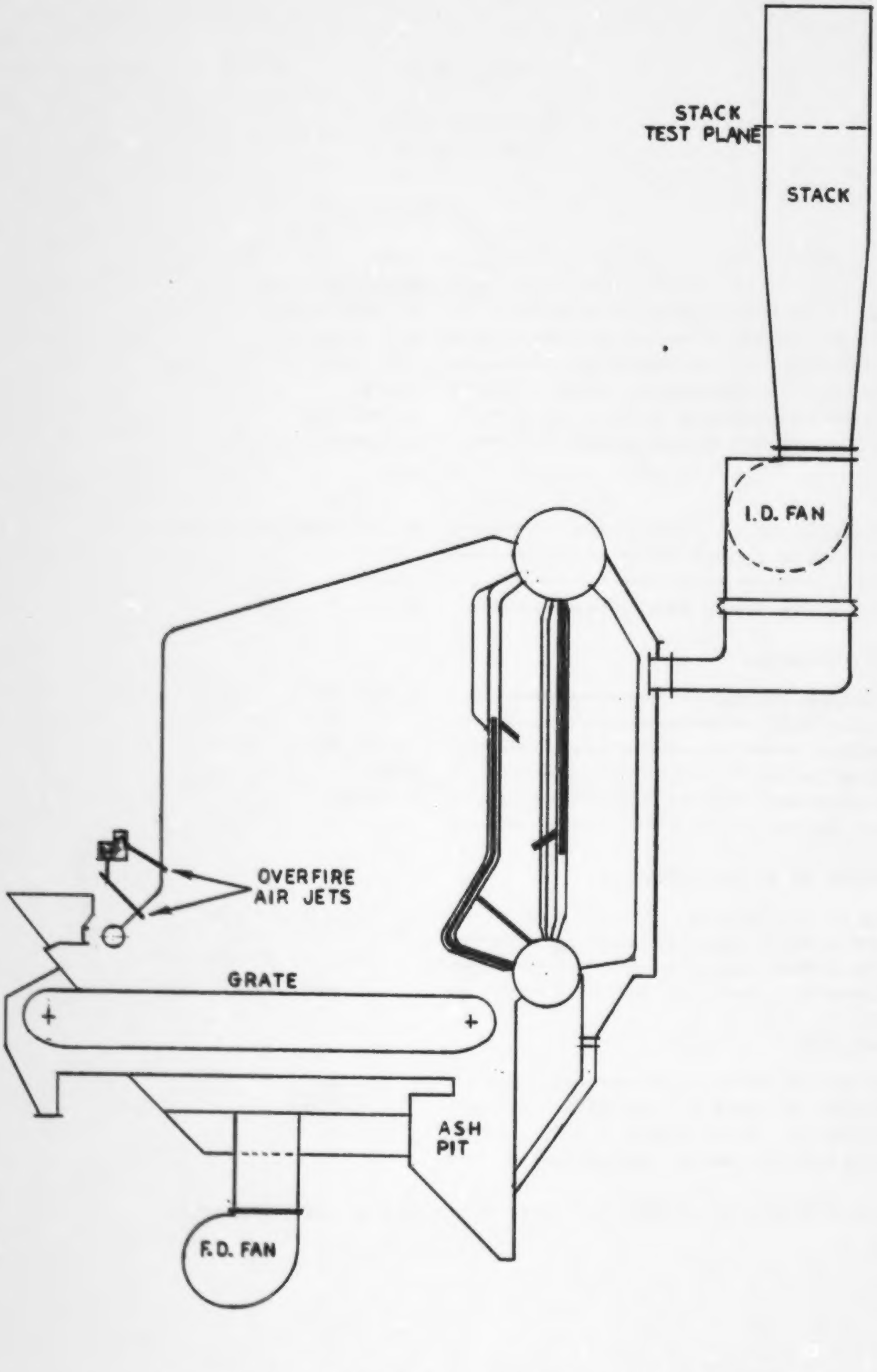
STACK TEST PLANE
STACK
I.D. FAN
OVERFIRE AIR JETS
GRATE
ASH PIT
F.D. FAN

Figure 4-3. Test Site I General Arrangement Drawing

KVB 4-15900-554

TABLE 4-5

EQUIPMENT DATA
TEST SITE: J

BOILER:	
Year Built	1977
Configuration	Multiple Pass
Rated Steaming Capacity	70,000 lb/hr
Design Pressure	250 psig
Actual Operating Pressure	150 psig
Feedwater Temperature	220°F
Steam Temperature	Saturated
Operating Air Temperature	Ambient
STOKER:	
Classification	Mass Fired Chain Grate
Effective Length	15.3 Ft
Width	14.0 Ft
Effective Grate Area	213.0 Ft^2
HEATING SURFACES:	
Furnace Volume	4,005 Ft^3
Water Wall	715 Ft^2
Boiler	7,745 Ft^2
Superheater	None
Economizer	Unknown
Air Heater	None
HEAT RATES AT RATED CAPACITY:	
Input to Furnace	84,140,000 Btu/hr
Grate Width Heat Release	6,010,000 Btu/hr-ft
Grate Heat Release	395,000 Btu/hr-ft^2
Furnace Liberation	21,000 Btu/hr-ft^3
OVERFIRE AIR:	
Location	Front Wall
Number of Jets x Pipe Size	15x1-5/8"
Elevation Above Grate	3.8 Ft
Inclination below Horizontal	15°
EMISSION CONTROL EQUIPMENT:	Mechanical Collector

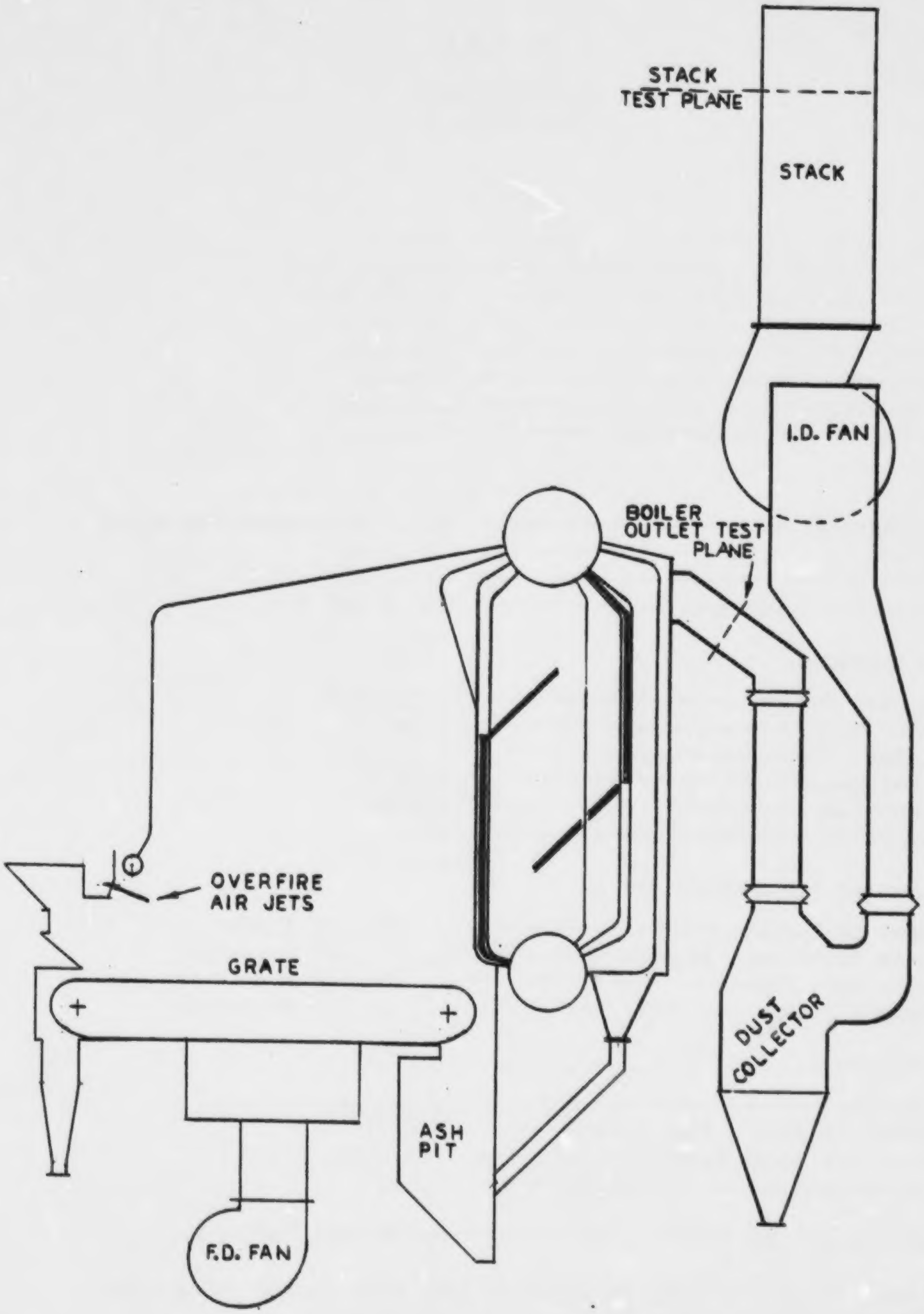
STACK
TEST PLANE
STACK
I.D. FAN
BOILER
OUTLET TEST
PLANE
OVERFIRE
AIR JETS
GRATE
DUST
COLLECTOR
ASH
PIT
F.D. FAN

Figure 4-4. Test Site J General Arrangement Drawing

KVB 4-15900-554

TABLE 4-6

EQUIPMENT DATA
TEST SITE: K

BOILER:

Year Built	1977
Configuration	Multiple Pass
Rated Steaming Capacity	50,000 lb/hr
Design Pressure	200 psig
Actual Operating Pressure	125 psig
Feedwater Temperature	Unknown
Steam Temperature	Saturated
Operating Air Temperature	Ambient

STOKER:

Classification	Mass Fired Traveling Grate
Effective Length	16.0 Ft
Width	10.0 Ft
Effective Grate Area	160.0 Ft^2

HEATING SURFACES:

Furnace Volume	2,614 Ft^3
Water Wall	1,143 Ft^2
Boiler	5,526 Ft^2
Superheater	None
Economizer	Unknown
Air Heater	None

HEAT RATES AT RATED CAPACITY: *

Input to Furnace	65,000,000 Btu/hr
Grate Width Heat Release	6,500,000 Btu/hr-ft
Grate Heat Release	406,000 Btu/hr-ft^2
Furnace Liberation	24,900 Btu/hr-ft^3

OVERFIRE AIR:

Location	Front Wall
Number of Jets x Pipe Size	8x1½"
Elevation Above Grate	5.0 Ft
Inclination below Horizontal	30°

EMISSION CONTROL EQUIPMENT:	Mechanical Collector

* Heat rates are based on measured Fuel Flow data at this site, manufacturers design data was not available.

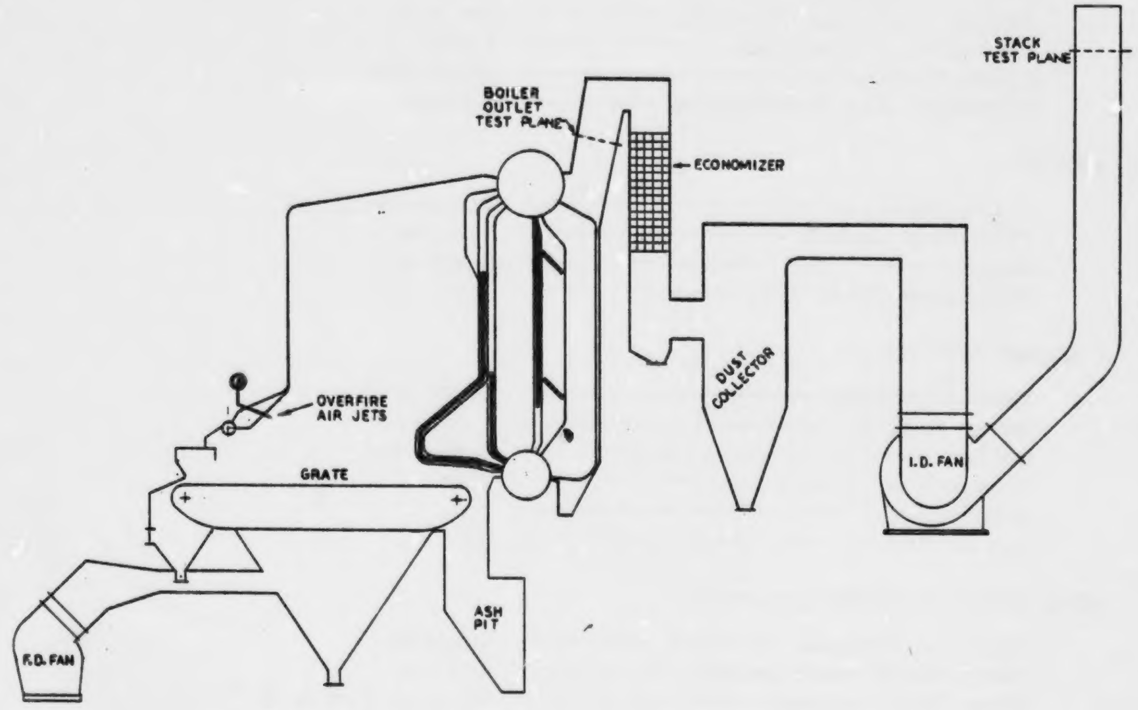
BOILER OUTLET TEST PLANE
ECONOMIZER
STACK TEST PLANE
OVERFIRE AIR JETS
GRATE
DUST COLLECTOR
I.D. FAN
ASH PIT
F.D. FAN

Figure 4-5. Test Site K General Arrangement Drawing

TABLE 4-7

EQUIPMENT DATA
TEST SITE: L2

BOILER:	
Year Built	1965
Configuration	Multiple Pass
Rated Steaming Capacity	30,000 lb/hr
Design Pressure	Unknown
Actual Operating Pressure	125 psig
Feedwater Temperature	212°F
Steam Temperature	Saturated
Operating Air Temperature	Ambient
STOKER:	
Classification	Vibrating Grate
Effective Length	Unknown
Width	Unknown
Effective Grate Area	123.1 Ft^2
HEATING SURFACES:	
Furnace Volume	1,665 Ft^3
Water Wall	1,641 ft^2
Boiler	4,514 ft^2
Superheater	None
Economizer	None
Air Heater	None
HEAT RATES AT RATED CAPACITY:	
Input to Furnace	Unknown
Grate Width Heat Release	Unknown
Grate Heat Release	300,000 $Btu/hr\text{-}ft^2$
Furnace Liberation	30,000 $Btu/hr\text{-}ft^3$
OVERFIRE AIR:	
Location	Unknown
Number of Jets x Pipe Size	Unknown
Elevation Above Grate	Unknown
Inclination below Horizontal	Unknown
EMISSION CONTROL EQUIPMENT:	Mechanical Collector

TABLE 4-8

EQUIPMENT DATA
TEST SITE: L4

BOILER:	
Year Built	1969
Configuration	Multiple Pass
Rated Steaming Capacity	27,000 lb/hr
Design Pressure	250 psig
Actual Operating Pressure	150 psig
Feedwater Temperature	220°F
Steam Temperature	Saturated
Operating Air Temperature	Ambient
STOKER:	
Classification	Chain Grate
Effective Length	11.9 Ft
Width	9.0 Ft
Effective Grate Area	107 Ft^2
HEATING SURFACES:	
Furnace Volume	1,315 Ft^3
Water Wall	920 Ft^2
Boiler	2,930 Ft^2
Superheater	None
Economizer	None
Air Heater	None
HEAT RATES AT RATED CAPACITY:	
Input to Furnace	Unknown
Grate Width Heat Release	Unknown
Grate Heat Release	333,000 Btu/hr-ft^2
Furnace Liberation	30,300 Btu/hr-ft^3
OVERFIRE AIR:	
Location	Front Wall
Number of Jets x Pipe Size	9x1¼"
Elevation Above Grate	3.5 Ft
Inclination below Horizontal	15°
EMISSION CONTROL EQUIPMENT:	Mechanical Collector

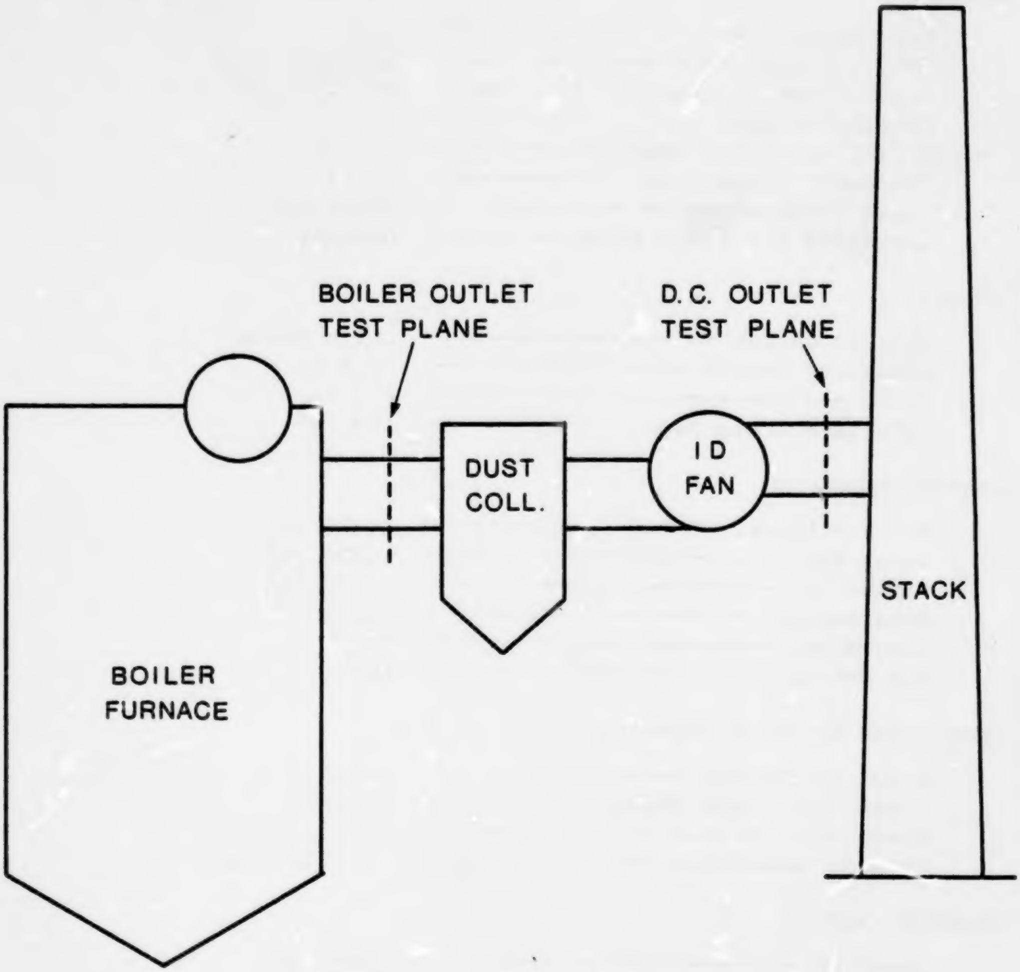
BOILER OUTLET
TEST PLANE
D.C. OUTLET
TEST PLANE
DUST
COLL.
I D
FAN
STACK
BOILER
FURNACE

Figure 4-6. Boiler Schematic for Test Sites L2 and L4.

4.2 PERFORMANCE AT FULL LOAD

This section presents, in graphical format, the emissions and efficiency of seven mass fired overfeed stokers operated at or near full load. For the purposes of this report, full load is defined as the upper 10% of the load range obtainable at the time of testing. For Sites H, I, J and K this represents 90 to 100% of nameplate rating. At Test Site D, however, the maximum obtainable load was 89% of nameplate because of draft losses incurred from a retrofit dust collector. Thus, loads above 80% of design were considered full load at Site D. At Sites L2 and L4 testing was conducted at a single operating condition representing 85% and 78% of steaming capacity, respectively. Although the data from these two tests are included in this section, their reduced loading should be kept in mind.

The capacity range of the data presented in this section, and the number of tests within that range, are given in Table 4-9.

TABLE 4-9

CAPACITY RANGE AND DATA BASE FOR FULL LOAD
TESTS ON SEVEN MASS FIRED OVERFEED STOKERS

	Percent Capacity Range	Number of Tests	
		Gaseous	Particulate
Site D	86-89	9	6
Site H	96-102	10	3
Site I	98-104	15	4
Site J	93-103	8	3
Site K	95-102	9	7
Site L2	85	1	1
Site L4	78	1	1
	TOTALS	53	25

The data are represented by bar graphs which indicate the minimums, maximums and averages of the full load data. These graphs give an indication of how much the data varied between units and within each individual unit. The range of data shown is representative of normal variations experienced in day-to-day operation.

Extremes should be treated with caution when interpreting these data. There is a certain degree of scatter, or uncertainty, to the data which must be taken into account. Thus, for example, if a certain unit emitted a very low particulate loading during one test, it does not follow that this unit can operate continuously at the low particulate loading by simply duplicating the stoker settings of the test.

Emission Factors. Environmental Protection Agency publication AP-42, Compilation of Air Pollutant Emission Factors, Third Edition, contains factors used for predicting emissions from non-spreader stokers as well as spreader stokers.

The data from this test program have been converted to the same units used in AP-42 to obtain a set of measured emission factors for each site. These factors are presented in Table 4-10.

TABLE 4-10

EMISSION FACTORS FOR MASS FIRED OVERFEED STOKERS FIRING BITUMINOUS COAL

	Uncontrolled Particulates lb/ton	Nitrogen Oxides lb/ton
Site D	3.6 A	7.2
Site H	3.3 A	9.4
Site I	3.8 A	7.1
Site J	3.6 A	9.3
Site K	3.7 A	8.4
Site L2	1.1 A	NA
Site L4	1.6 A	NA
AVERAGE, °F (D, H, I, J & K)	3.6 A	8.3
AP-42	5 A	NA

The data clearly show that the emission factor "5A" is too high for these stokers firing the coals they were firing. The emissions did not deviate very much from their 3.6 A average.

It is equally evident that coal ash is not the primary variable affecting particulate loading. At Site K, three forms of coal from the same mine were fired in the same boiler with widely varying emission levels. The unwashed coal had an emission factor of 3.7 A as shown in Table 4-10. This same coal when washed, produced lower particulate yet had a greater emission factor of 4.9 A. In this case, the coal ash was reduced more than the particulates were by the process of washing the coal. When the washed coal was crushed to increase the fines content, the emission factor rose to 7.7 A. This would indicate that coal fines play an equally important role in determining particulate loading. This subject is discussed further in Section 4.5, Response to Coal Analysis and Sizing.

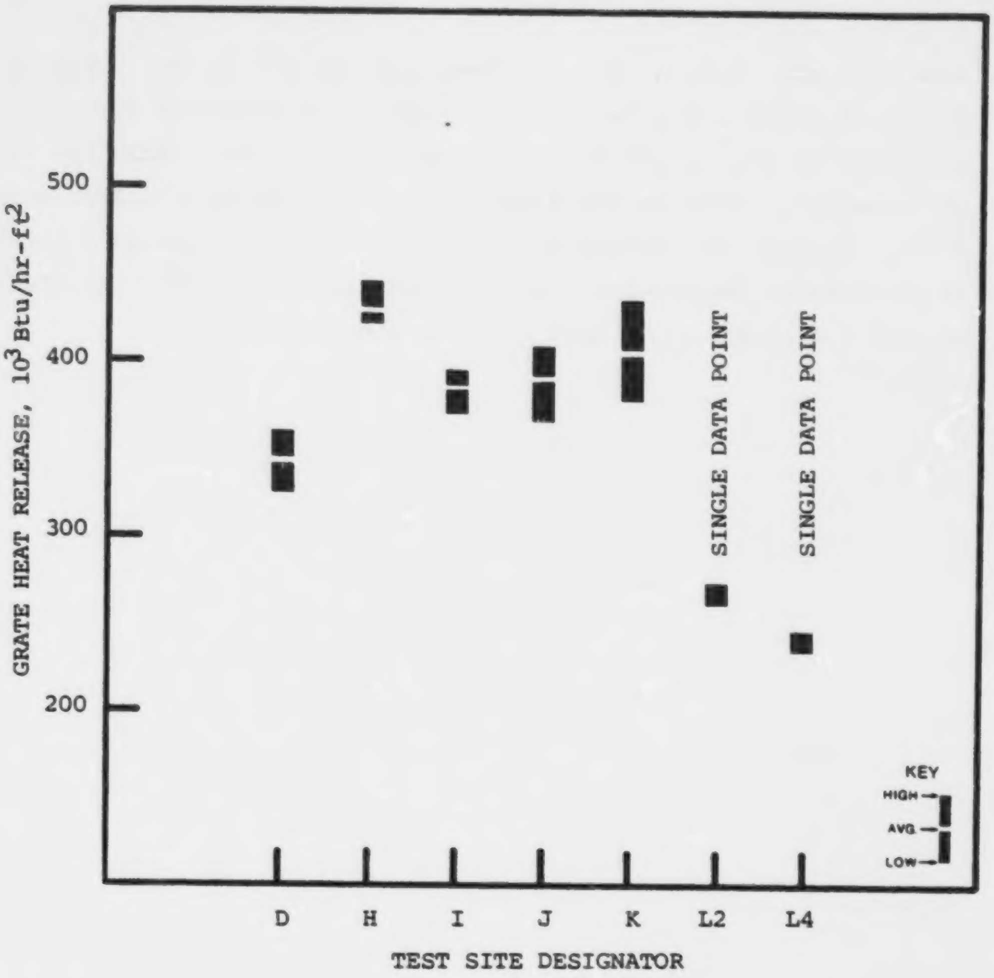

Figure 4-7. Grate Heat Release Rates of Seven Mass Fired Overfeed Stokers Fired at or Near Full Load.

The ranges of grate heat release rate shown here represent full load operation as defined in Table 4-9. All seven mass fired overfeed stokers were designed within the guidelines set by ABMA which specify a maximum grate heat release of 500,000 Btu/hr-ft^2 effective air admitting grate area for this class of stoker. Note that Test Site D was designed for 401x10^3 Btu/hr-ft^2, but achieved only 80% of this rate due to draft losses from a retrofit dust collector. Test Sites L2 and L4 were tested once each at a reduced load. The design grate heat release rates for each stoker in units of 10^3 Btu/hr-ft^2 are: D-401, H-425, I-377, J-395, K-406, L2-300, L4-333.

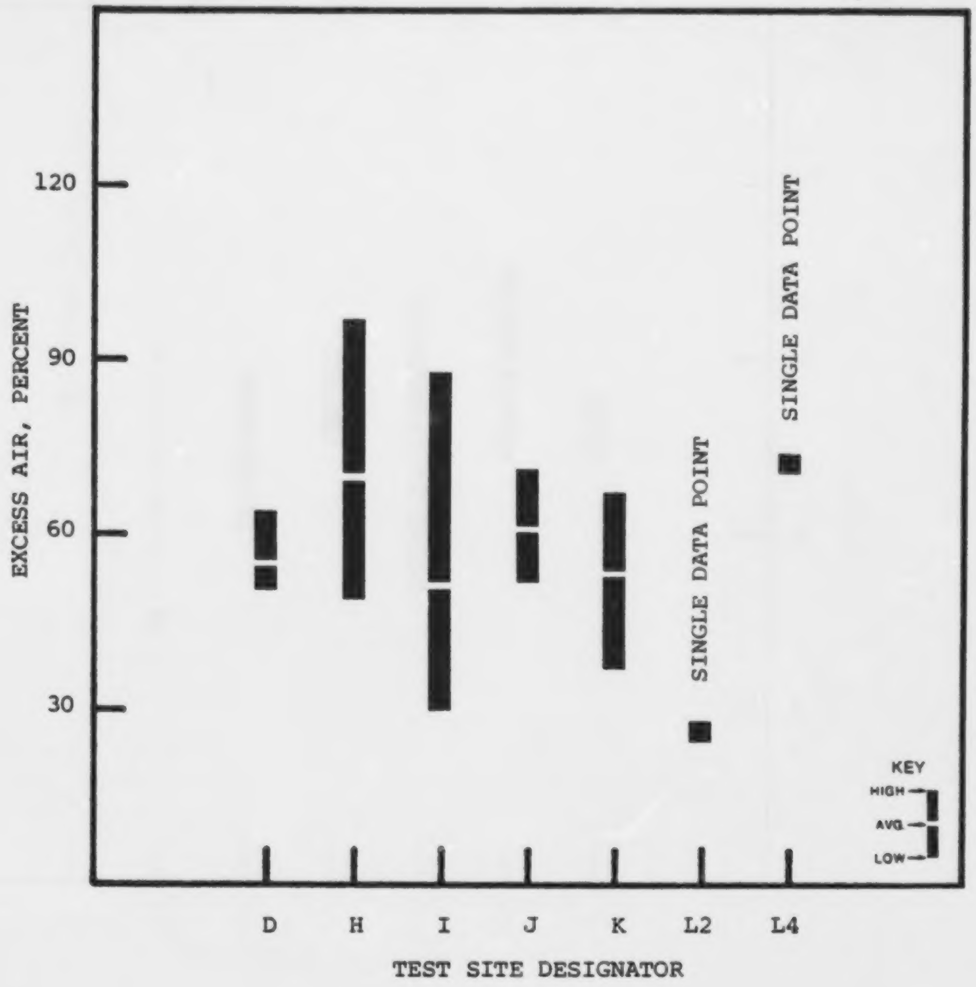

Figure 4-8. Excess Air Operating Levels of Seven Mass Fired Overfeed Stokers Fired at or near Full Load.

Excess air ranged from 26% to 97% in these tests. The averages for the five extensively tested sites ranged from 51% to 70%. Excess air was computed from flue gas analysis obtained at the boiler outlets of Sites D, J and K, and from the stack at Sites H, I, L2 and L4. As a reference, 60% excess air is approximately equal to 8% O_2.

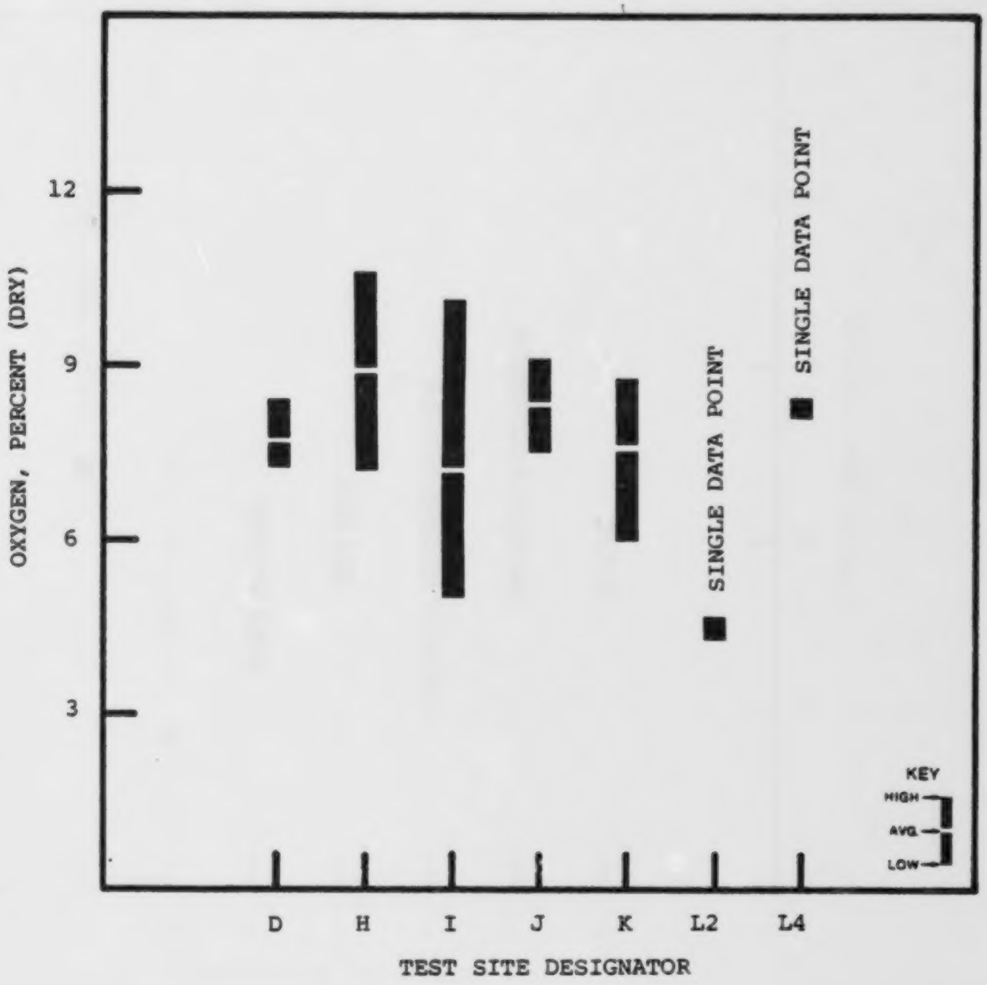

Figure 4-9. Excess Oxygen Operating Levels of Seven Mass Fired Overfeed Stokers Fired at or Near Full Load.

Flue gas oxygen was measured on a dry basis. It ranged from 4.5% to 10.6% overall. The averages for the five extensively tested sites ranged from 7.2% to 8.9%.

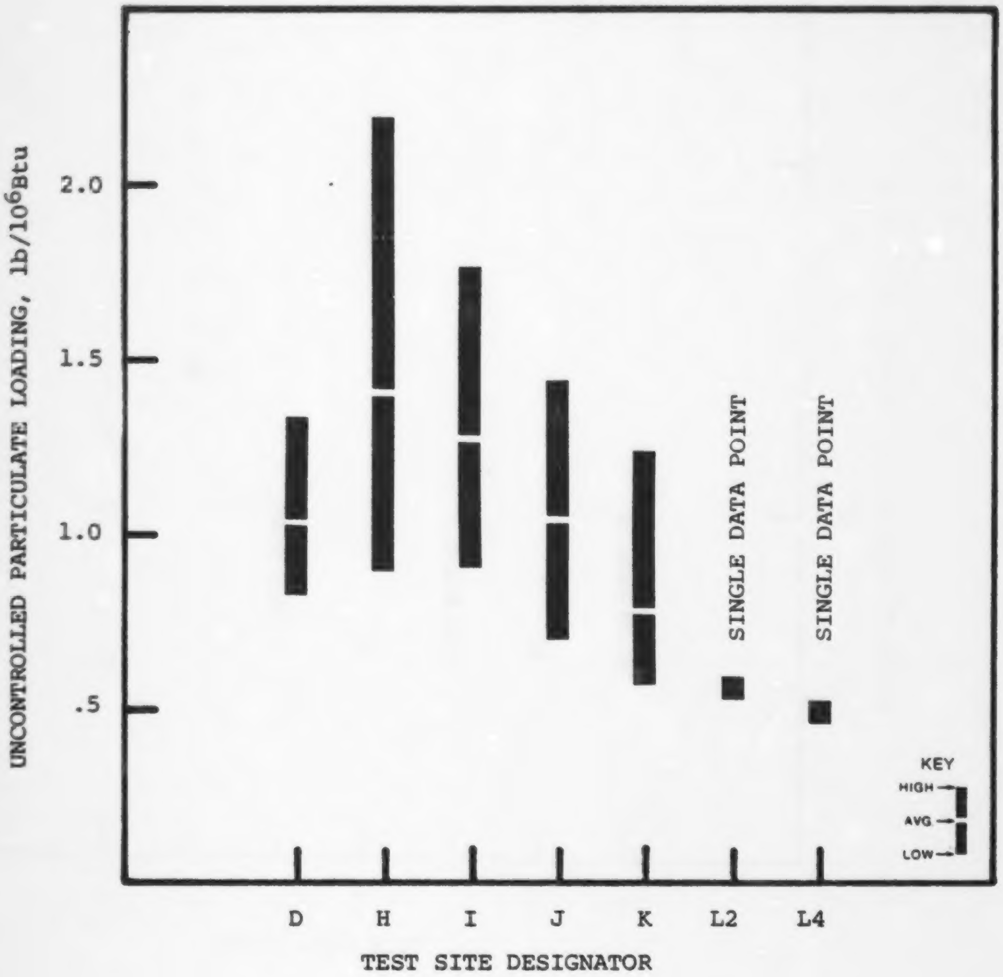

Figure 4-10. Uncontrolled Particulate Loadings of Seven Mass Fired Overfeed Stokers Fired at or Near Full Load.

Uncontrolled particulate loadings ranged from .57 lb/10^6Btu to 2.2 lb/10^6 on the five extensively tested mass fired overfeed stokers. The averages for these same five stokers ranged from .78 to 1.4 lb/10^6 Btu. Site L2 and L4 had lower particulate loadings of .56 and .50 lb/10^6 Btu, respectively, but these were obtained at lower loads of 85% and 78% of design capacity, respectively. The site L2 and L4 particulate data is not out of line when compared with data obtained at the same grate heat release from the other stokers.

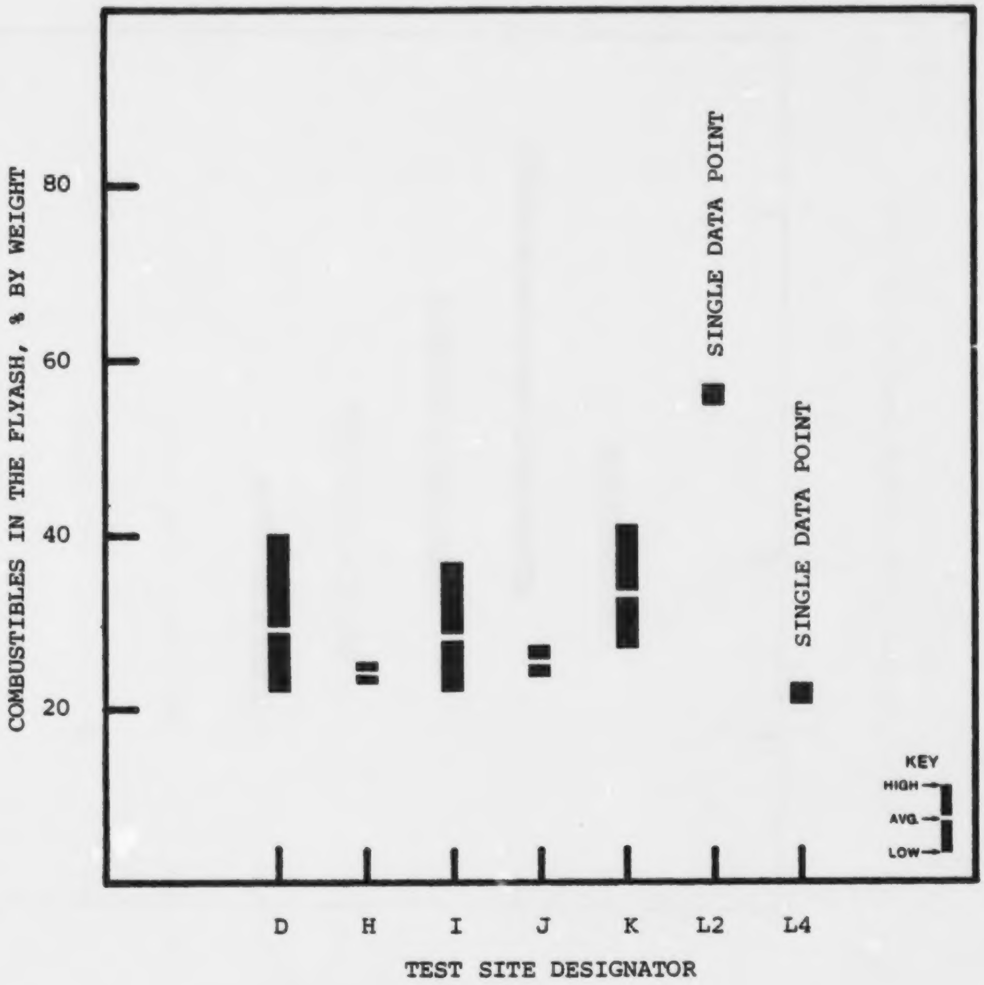

Figure 4-11. Percentage of Combustible Material in the Flyash of Seven Mass Fired Overfeed Stokers Fired at or Near Full Load.

Flyash collected at the uncontrolled particulate sampling location of the five extensively tested sites contained between 22% and 41% combustible material. The averages for these same five sites ranged from 24% to 33%. The flyash samples collected at Sites L2 and L4 were obtained from the dust collector hoppers rather than the boiler outlets.

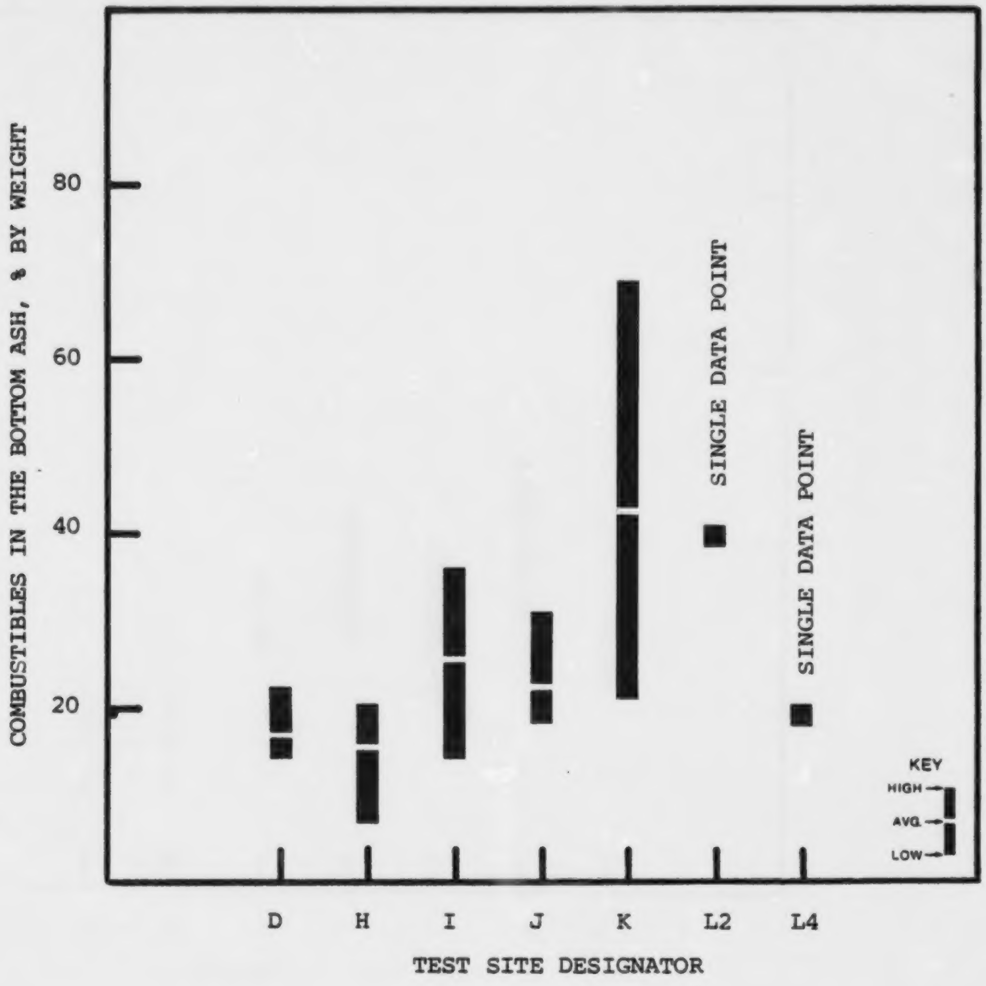

Figure 4-12. Percentage of Combustible Material in the Bottom Ash of Seven Mass Fired Overfeed Stokers Fired at or Near Full Load.

The percentage of combustible material in the bottom ash ranged from 7% to 69%. The averages for Sites D, H, I, and J ranged from 21% to 31%. For some reason, Site K's bottom ash combustibles were higher than the others, averaging 43%.

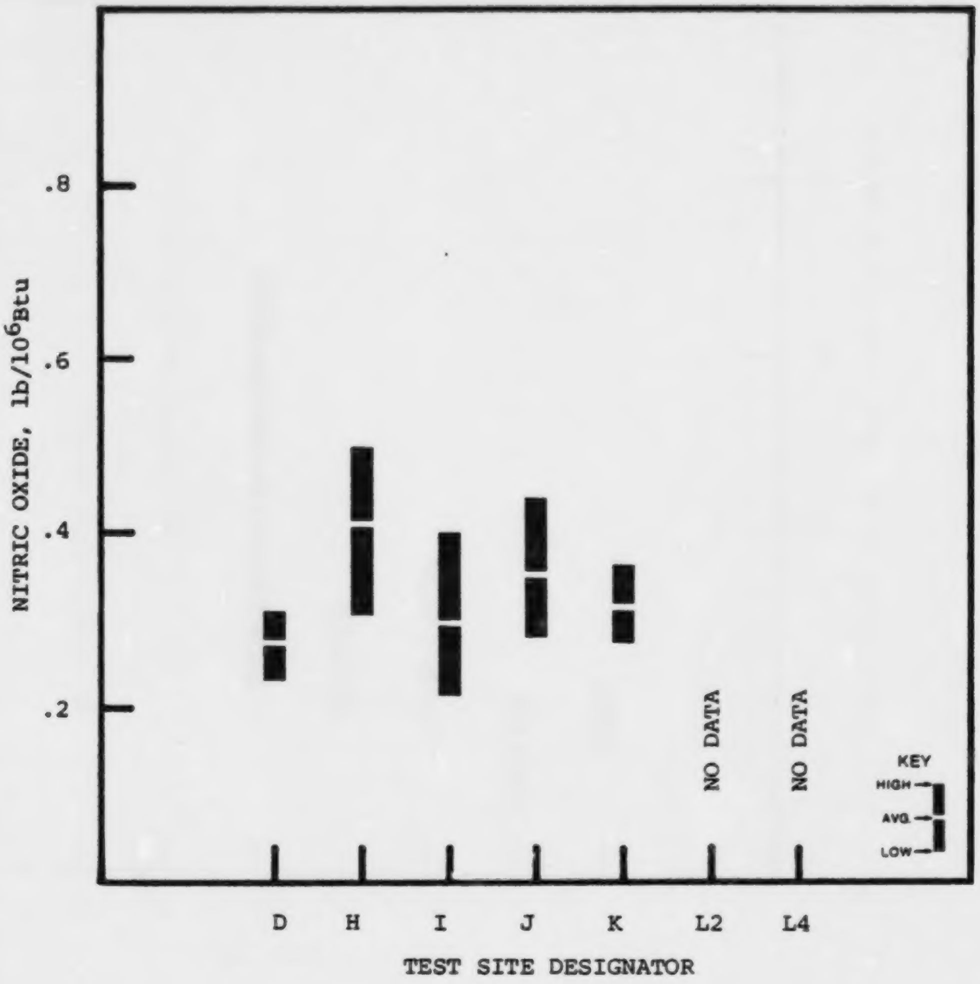

Figure 4-13. Nitric Oxide Emissions of Five Mass Fired Overfeed Stokers Fired at or Near Full Load.

Nitric oxide emissions ranged from .21 to .50 lb/10^6Btu computed as NO_2. Site averages ranged from .27 to .41 lb/10^6Btu. Some of the variations between sites are the result of different excess air operating levels. For example, Site H was operated at an average excess air of 70% compared to 51% for Site I. As a result, Site H's NOx emissions were higher.

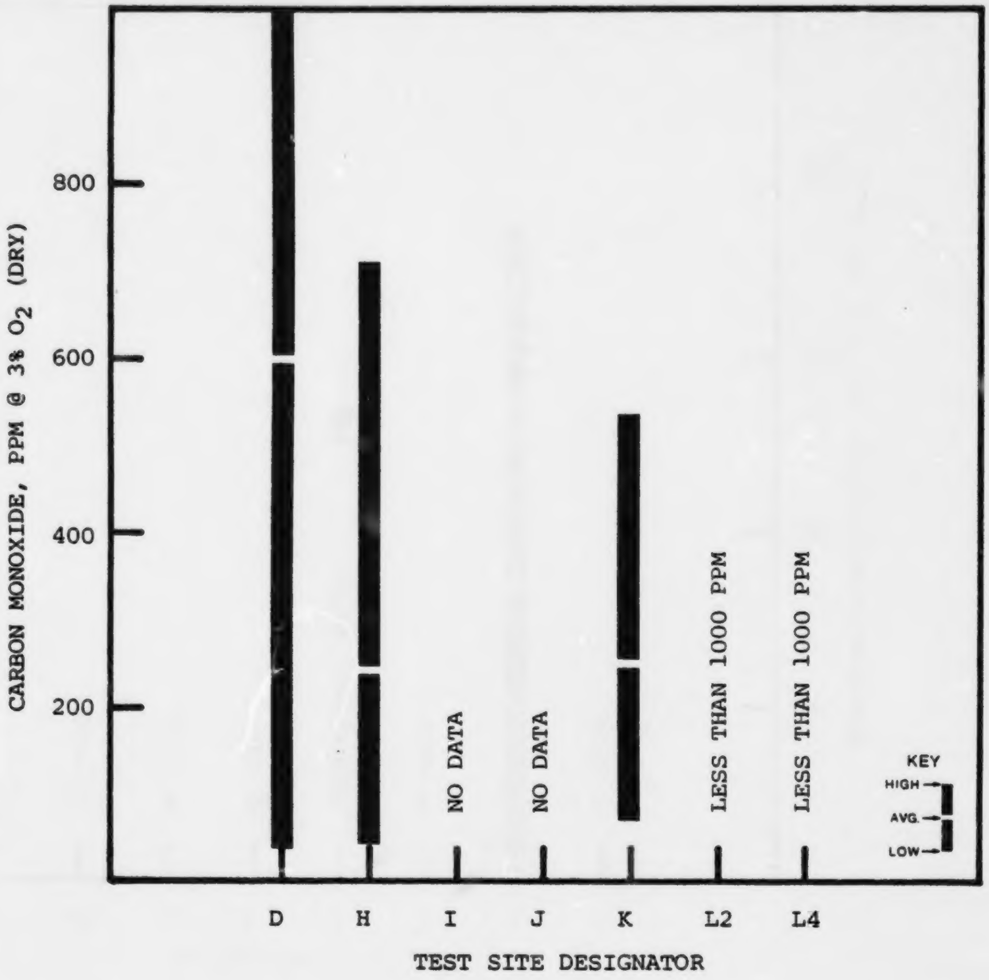

Figure 4-14. Carbon Monoxide Emissions of Five Mass Fired Overfeed Stokers Fired at or Near Full Load.

Carbon monoxide concentrations were highly sensitive to combustion conditions. They were highest near full load under low excess air conditions, or when overfire air was reduced too much. At Site D, carbon monoxide concentration exceeded 2000 ppm during one low overfire air test. In all other tests, they remained below 900 ppm. At Sites L2 and L4, CO was measured with an Orsat gas analyzer and found to be less than 1000 ppm (0.1%) which is the minimum detection limit of this instrument. The CO monitor was out of service at Sites I and J.

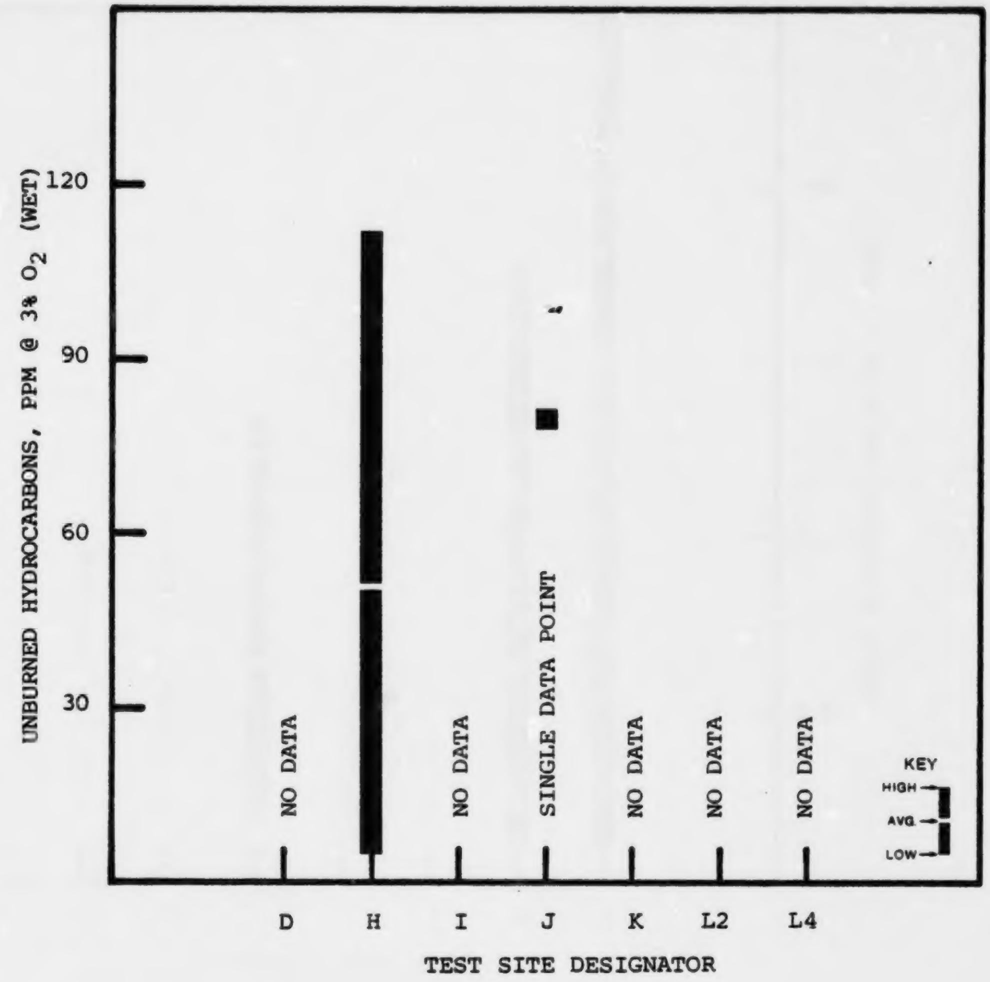

Figure 4-15. Unburned Hydrocarbon Emissions of Two Mass Fired Overfeed Stokers Fired at or Near Full Load.

Unburned hydrocarbons (HC) were successfully measured at only two of the five extensively tested mass fired overfeed stokers. A troublesome flame ionization hydrocarbon monitor and problems with a heated sample line prevented these measurements from being made on the other three stokers. The data ranged from 5 ppm to 112 ppm (wet) corrected to 3% O_2.

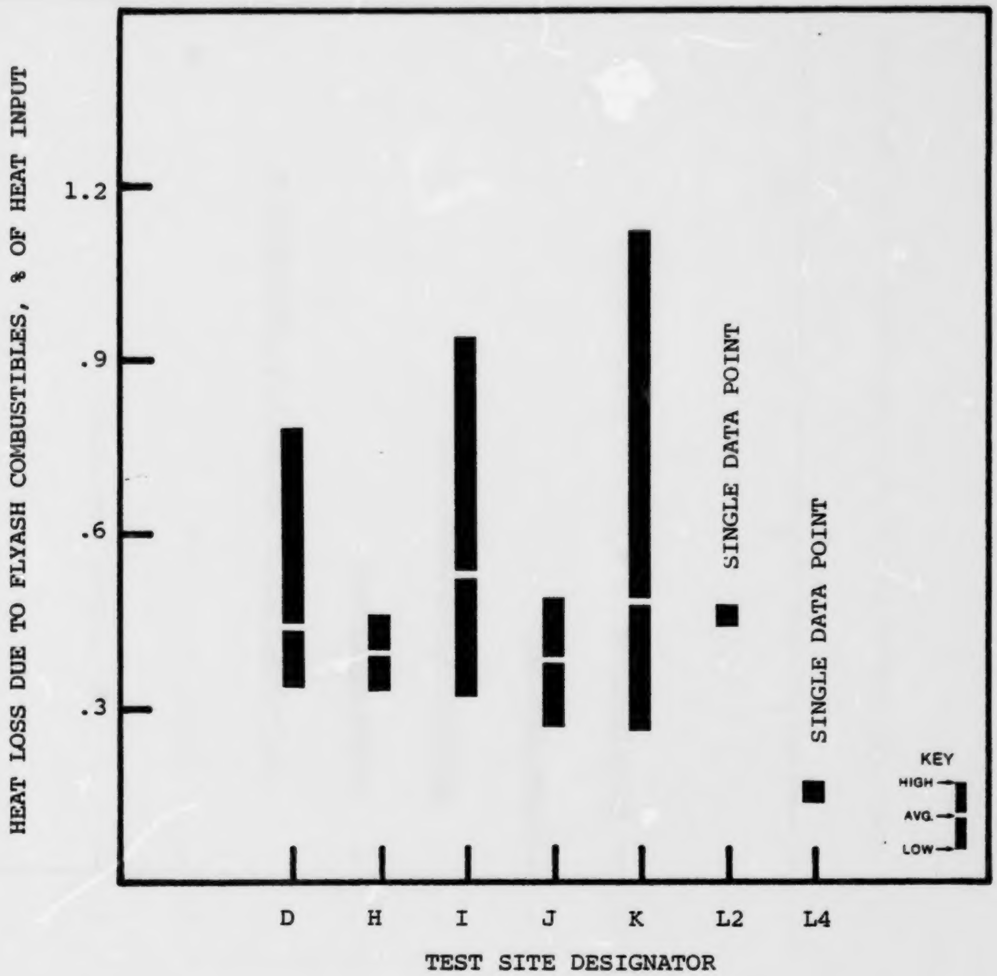

Figure 4-16. Heat Loss Due to Combustibles in the Flyash of Seven Mass Fired Overfeed Stokers Fired at or Near Full Load.

Heat loss due to combustibles in the flyash ranged from .16% to 1.1%. The averages for the five extensively tested stokers ranged from .35% to .52%. These heat loss calculations are based on an assumed heating value of the combustible material of 14,250 Btu/lb. The Flyash was not directly analyzed for its heating value.

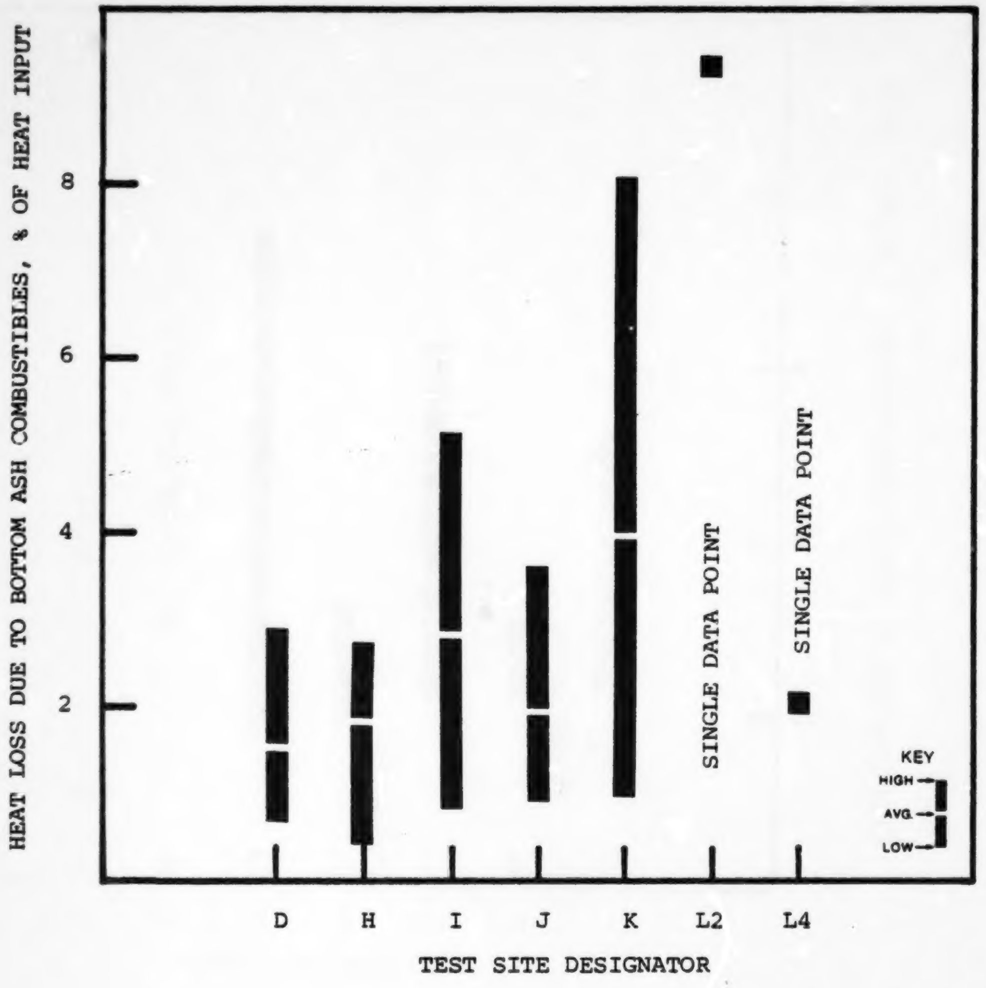

Figure 4-17. Heat Loss Due to Combustibles in the Bottom Ash of Seven Mass Fired Overfeed Stokers Fired at or Near Full Load.

Heat loss due to combustibles in the bottom ash ranged from 0.4% to 9.4%. The averages of Sites D, H, I and J ranged from 1.4% to 2.8%. Test Site K averaged 4.0% due to its higher bottom ash combustible content. These heat loss calculations are based on an assumed heating value of the combustible material of 14,250 Btu/lb. The bottom ash was not directly analyzed for its heating value.

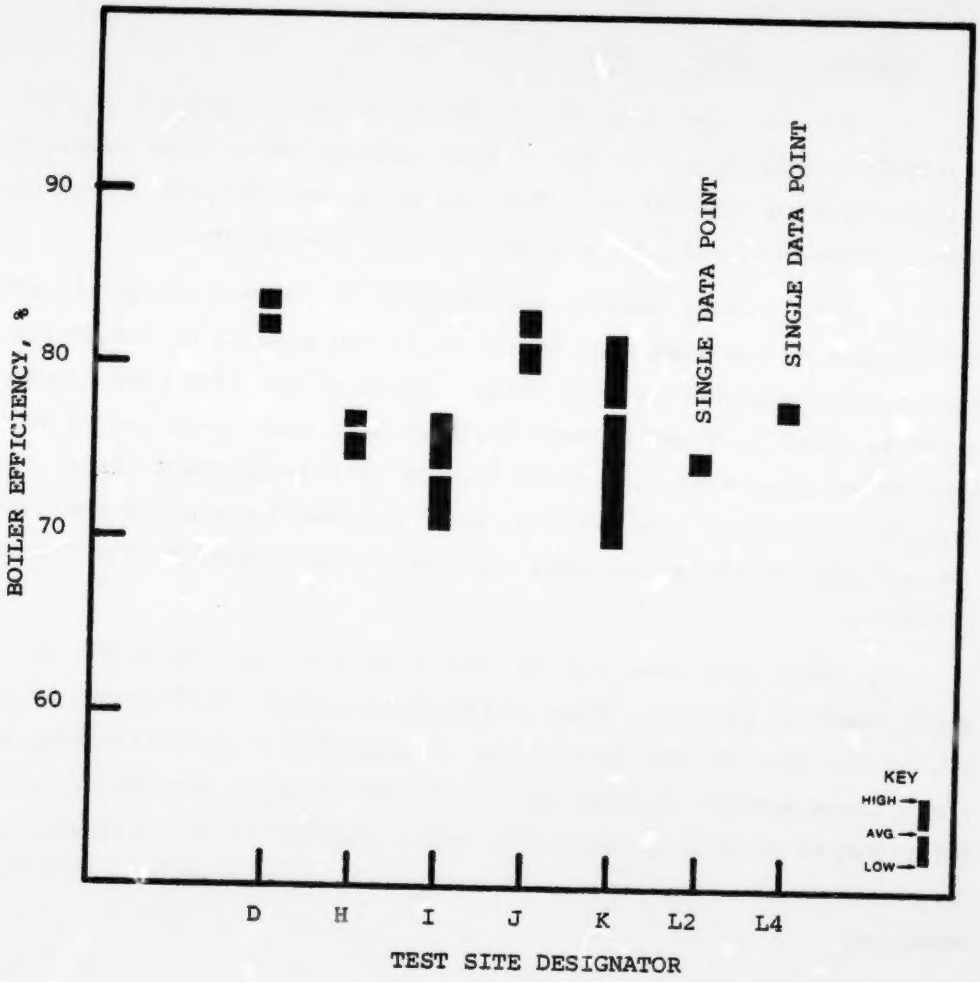

Figure 4-18. Boiler Efficiency of Seven Mass Fired Overfeed Stokers Fired at or Near Full Load.

Measured boiler efficiencies for these units ranged from 69.8% to 84.1%. Sites D, J and K, which were equipped with economizers, had the highest average efficiencies at 83.8%, 81.8% and 78.4%, respectively. Sites H and I, which did not have economizers, averaged 75.4% and 73.9% boiler efficiencies, respectively. Boiler efficiencies were determined by the ASME heat loss method (PTC 4.1).

4.3 RESPONSE TO HEAT RELEASE RATE

This section profiles the emissions and efficiency of five mass fired overfeed stokers as a function of heat release rate. Four measures of heat release rate are considered. They are grate heat release, front foot heat release, furnace liberation, and percent of steaming capacity.

Heat release rate is the quantity of thermal energy introduced into the furnace by the fuel each hour. It is the product of the hourly fuel rate and the fuel's higher heating value. Three of the five mass fired overfeed stokers, Sites H, I and J, were equipped with coal weigh lorrys which did not provide accurate fuel flow rates for the relatively short three-hour test periods. Therefore, heat release rate on these three units was taken to be the enthalpy of the steam times the steam flow divided by the fractional boiler efficiency.

Table 4-11 presents the design heat release rates for the five mass fired overfeed stokers. Their differences reflect differences in unit design. One of the aims of this section is to determine if a relationship exists between these design differences and the unit's emissions and efficiency. The other aim is to profile emissions and efficiency as heat release rate is varied on a given unit. The results of this study are presented in the following subsections.

TABLE 4-11

DESIGN HEAT RELEASE RATES

	Furnace Liberation Btu/hr-ft^3	Grate Heat Release Btu/hr-ft^2	Front Foot Heat Release Btu/hr-ft
Site D	29,300	401,000	6,630,000
Site H	32,300	425,000	4,580,000
Site I	24,400	377,000	6,800,000
Site J	21,000	395,000	6,010,000
Site K	24,900	406,000	6,500,000

4.3.1 Excess Air vs Heat Release Rate

The excess air requirement in stoker boilers is a function of heat release rate. At reduced heat release rates, more excess air is required to maintain good combustion.

Excess air profiles for the five mass fired overfeed stokers are shown in Figure 4-19. With the exception of Test Site K, they have similar slopes. As full load is approached, an increase of 100,000 Btu/hr-ft^2 is accompanied by an average 20% drop in excess air.

The larger stokers are able to operate at reduced excess air levels. This observation is illustrated in Figure 4-20 where the average as-found excess air operating levels, at 350,000 Btu/hr-ft^2, are compared with the grate areas. This same relationship was observed for the spreader stokers.

One possible explanation for this relationship was suggested in Section 3.3.1 when discussing the same observation on spreader stokers. That is, the larger units are likely to leak a smaller percentage of air through access doors and around the grate due to their smaller surface-to-volume ratio.

One more observation worth mentioning is the coal gate position, i.e., bed depth, as a function of load. Figure 4-21 shows this relationship for the four traveling grate and chain grate stokers. The fact that Site K was operated with a lower, static fuel bed than the others may relate to some of the differences in emissions observed for this unit. The coal gate position was not recorded during tests at Site D.

4.3.2 Particulate Loading vs Heat Release Rate

Uncontrolled particulate loading increased as heat release rate increased. The trends, as visually determined from data plots, are shown in Figure 4-22. Sites D, H and J showed a distinct increase in slope at high heat release rates. Sites I and K (washed coal only) had approximately linear relationships with grate heat release.

The relationship between uncontrolled particulate loading and heat release rate was also examined statistically. A line was fit to the data from each site using linear regression analysis. The slopes of these lines are presented in Table 4-12 along with the coefficient of correlation (r^2). The

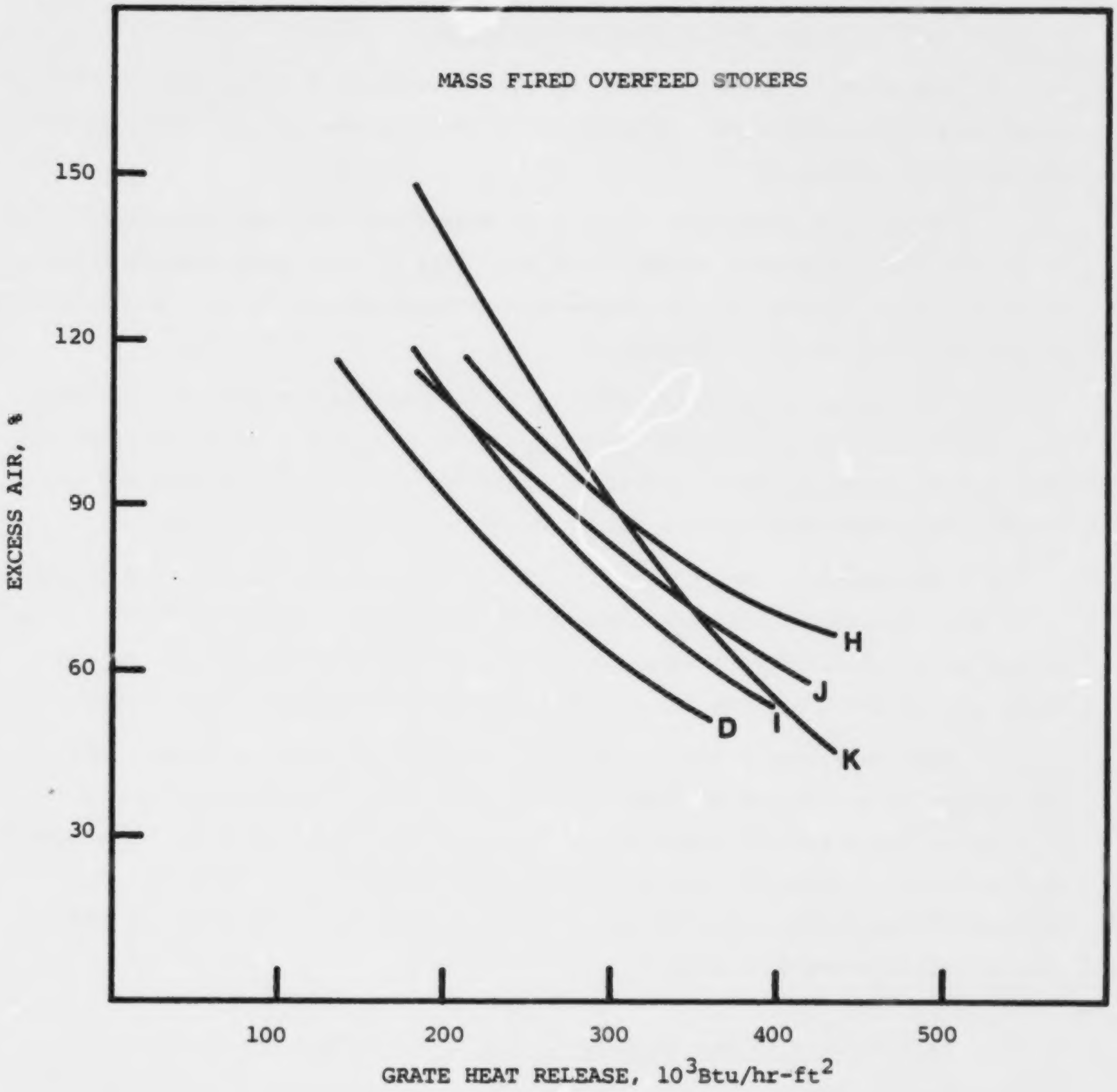

Figure 4-19. Excess Air Profiles for Five Mass Fired Overfeed Stokers. The Lines Represent Average As-Found Operating Conditions.

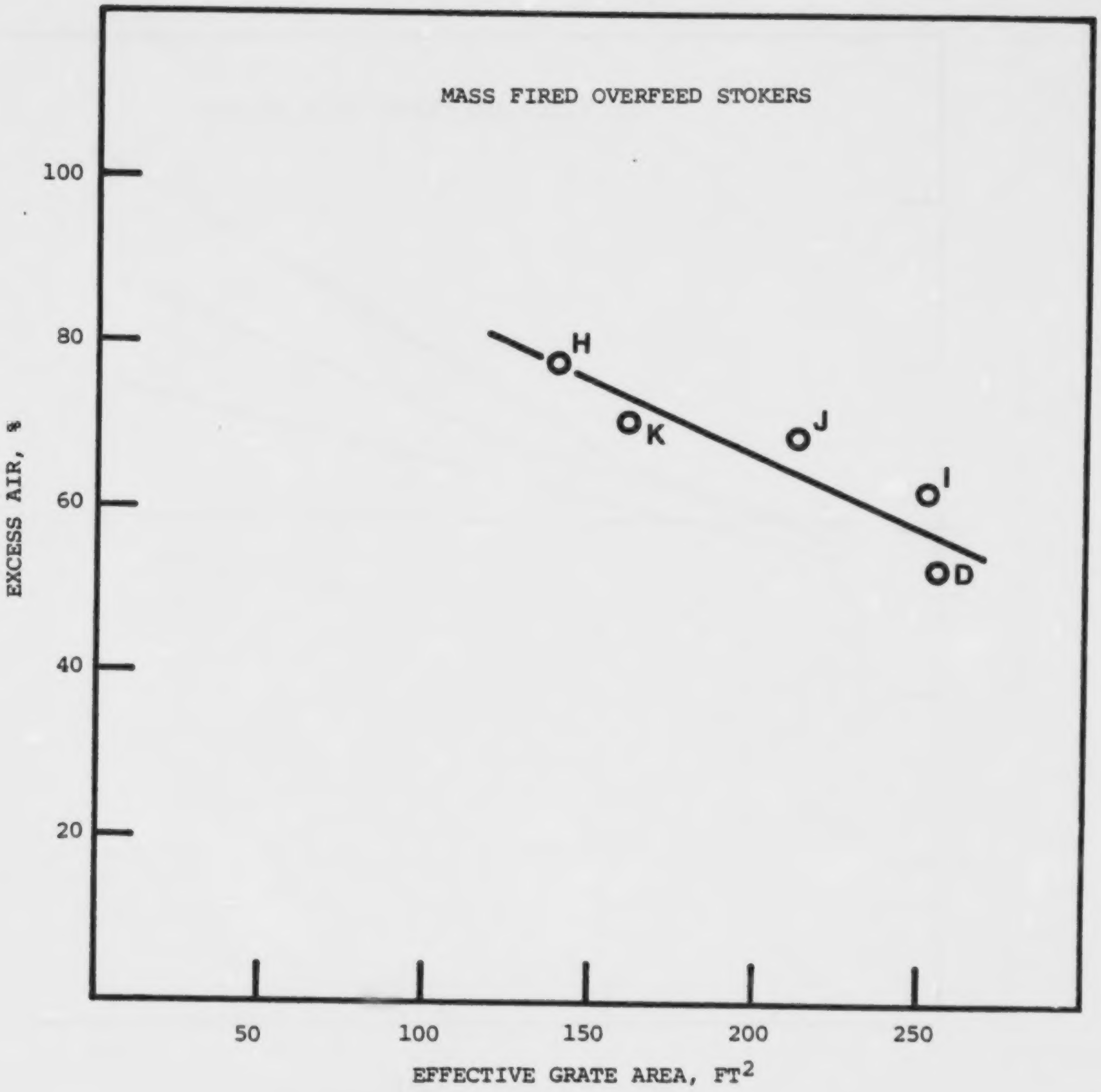

Figure 4-20. Excess Air Operating Levels of Five Mass Fired Overfeed Stokers Showing a Correlation with Size of the Grate. The Data Represents a Common Grate Heat Release of 350,000 Btu/hr-ft^2.

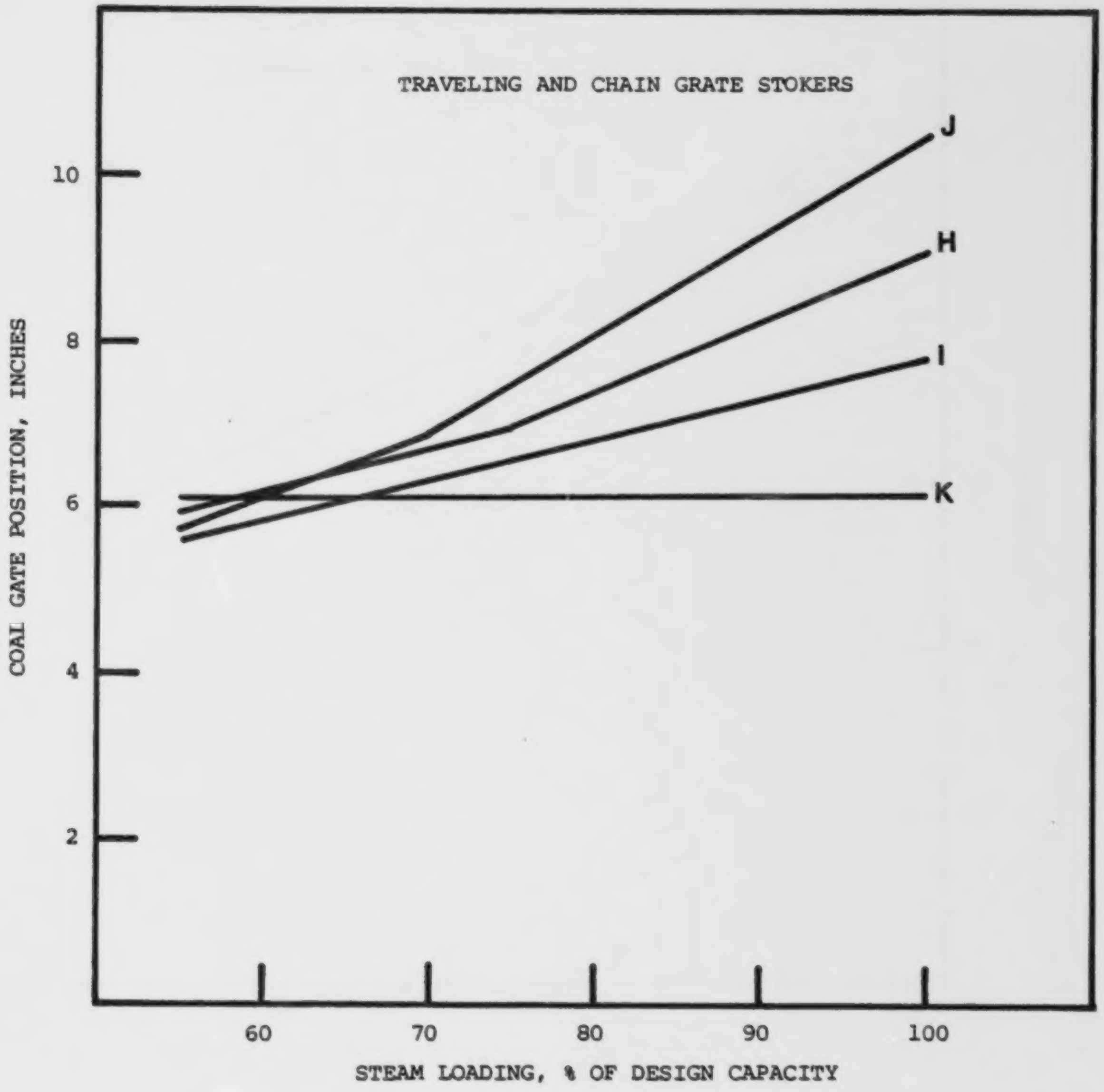

Figure 4-21. Coal Gate Position as a Function of Load for Four Traveling Grate and Chain Grate Stokers.

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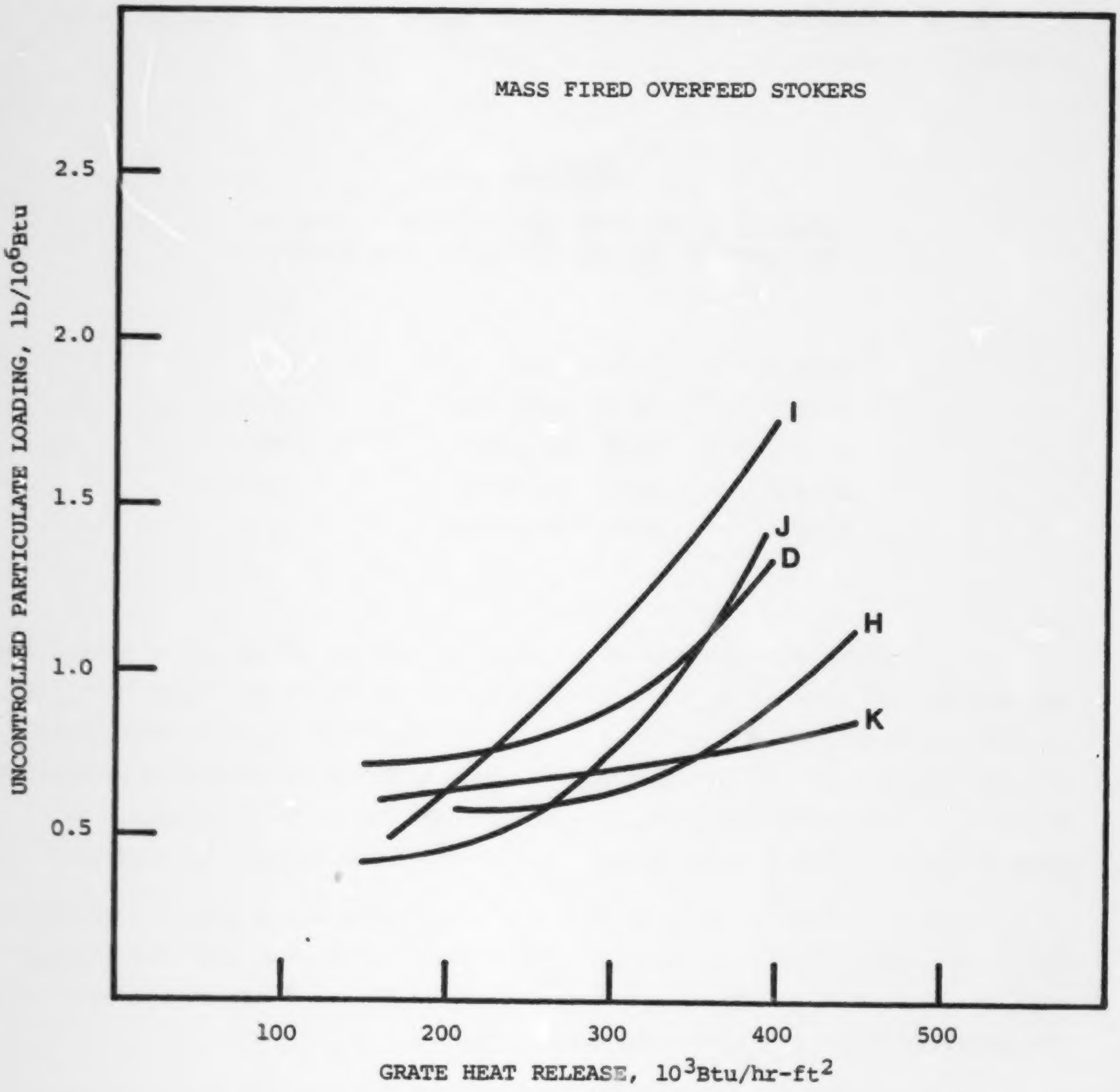

Figure 4-22. Uncontrolled Particulate Loading Profiles for Five Mass Fired Overfeed Stokers.

correlation coefficient indicates how well the data fit the equation, with 1.0 being a perfect fit.

TABLE 4-12

INCREASE IN UNCONTROLLED PARTICULATE LOADING FOR EACH 10^3 BTU/HR-FT^2 GRATE AREA INCREASE

		r^2
Site D	.0025 lb/10^6Btu	.52
Site H	.0020 lb/10^6Btu	.55
Site I	.0028 lb/10^6Btu	.28
Site J	.0027 lb/10^6Btu	.46
Site K	.0007 lb/10^6Btu	.11

The slope of uncontrolled particulate loading versus grate heat release was similar for Site D, H, I and J. This is evident both in Figure 4-22, and in Table 4-12 where it ranged from .20 to .28 lb/10^6Btu for each grate heat release increase of 100,000 Btu/hr-ft^2. Test Site K's uncontrolled particulate loading, on the other hand, was less sensitive to grate heat release. At Site K, the corresponding slope was .07 lb/10^6Btu per 100,000 Btu/hr-ft^2.

The uncontrolled particulate profile at Site K was also a function of coal properties. The data, shown in Figure 4-23, show that when the primary coal was crushed to increase its fines or not washed to increase its ash content the sensitivity to grate heat release increased.

Another variable affecting the particulate profiles was overfire air pressure. Sites H and I have dis-similar particulate profiles in Figure 4-22, which is based on normal operation. However, when the data from both sites are plotted together and segregated by overfire air pressure as in Figure 4-24, they begin to look quite similar. In other words, the differences in particulate loading between these two sites are related more to stoker-boiler operation than to design.

Boiler design, in terms of design heat release rates, did not correlate with particulate loading. Looking back at Table 4-11 we see that Test Site H stands out as having the highest design furnace liberation and grate heat release,

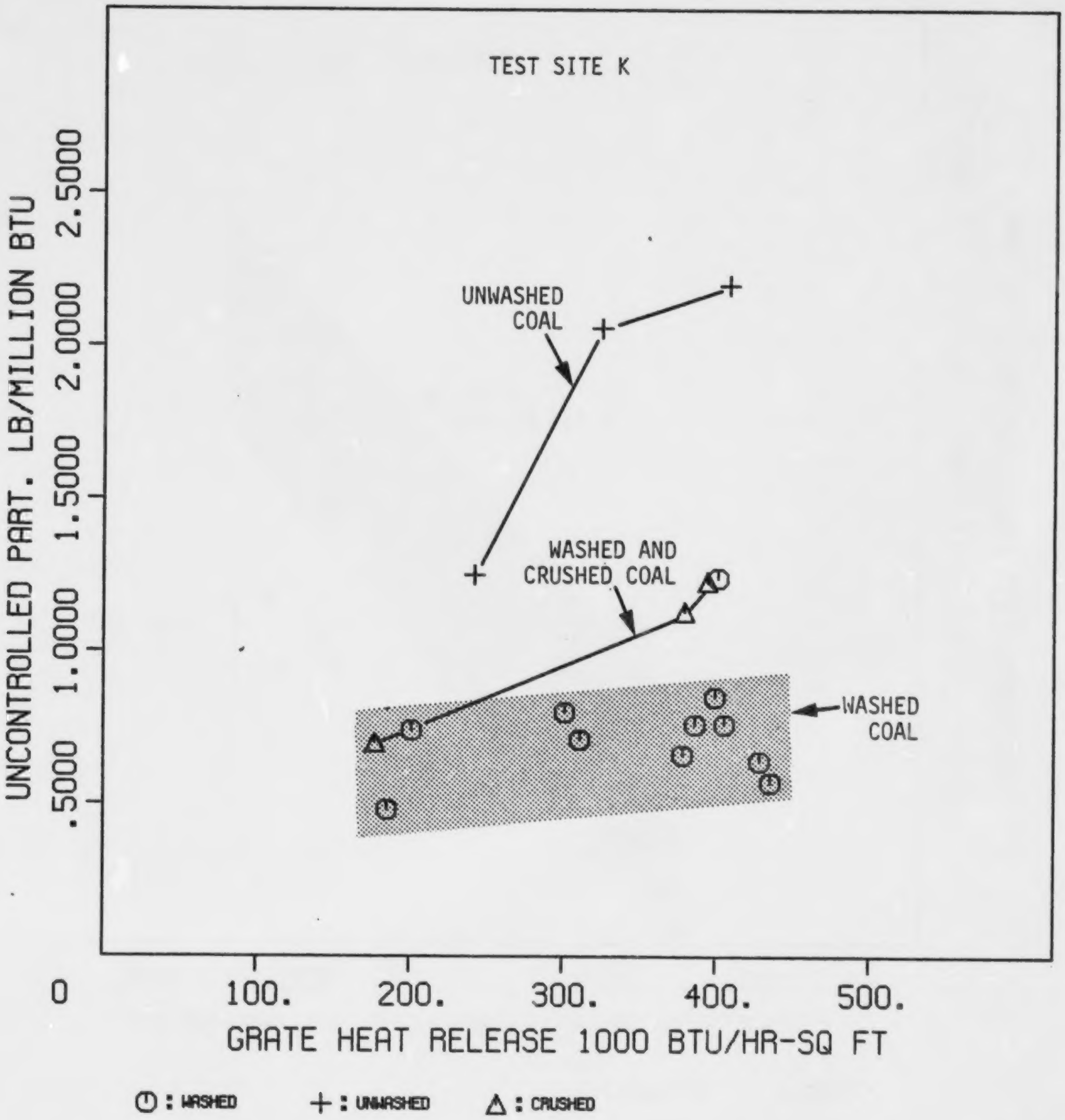

FIG. 4-23

UNCONTROLLED PART. VS. GRATE HEAT RELEASE

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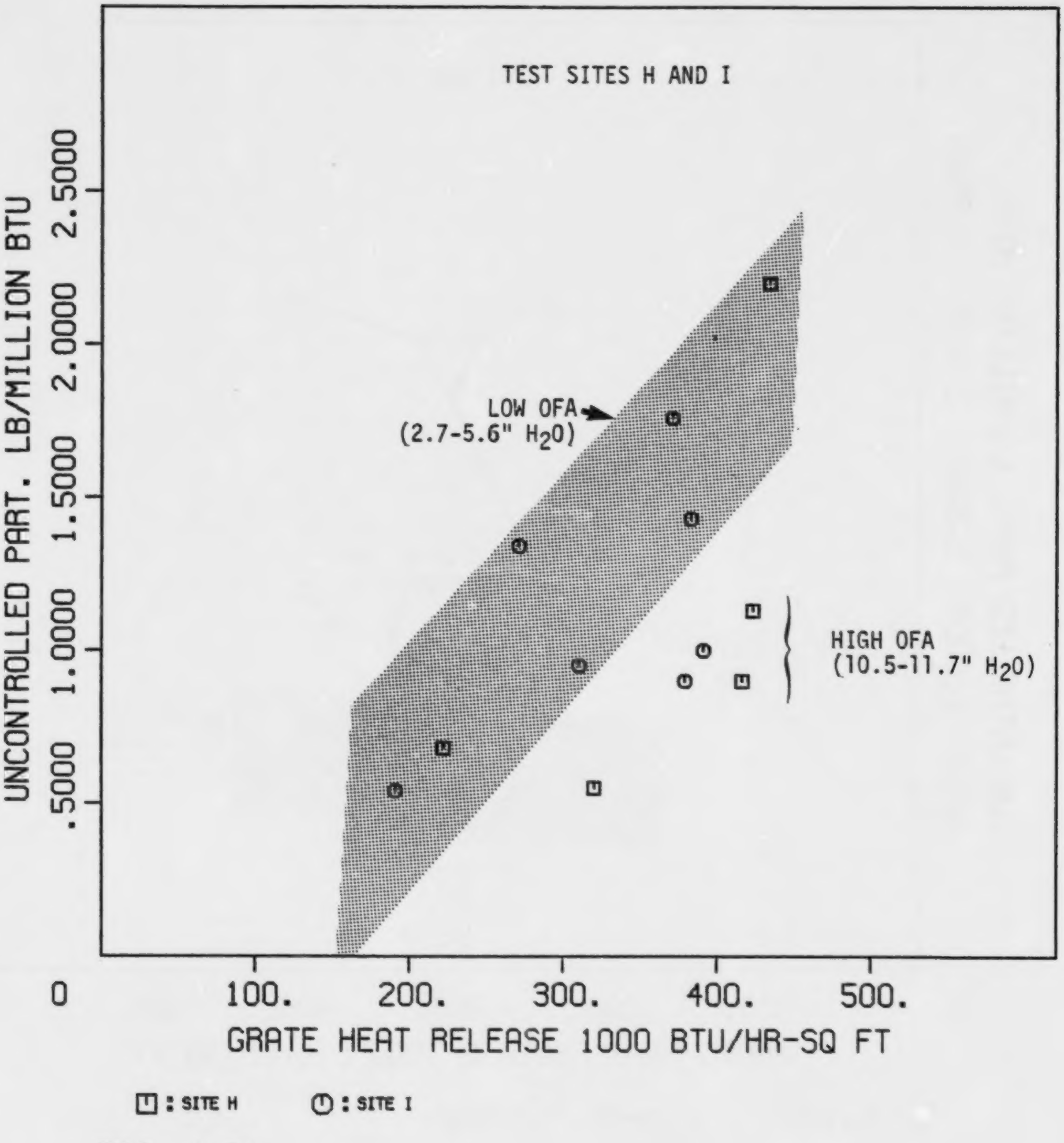


FIG. 4-24
UNCONTROLLED PART. VS. GRATE HEAT RELEASE

4-15900-554

and the lowest front foot heat release. Yet, Site H emitted particulates in the same range as the other stokers. In fact, most of the differences in particulate loading between these five stokers appear to be related to operating conditions and coal properties rather than stoker-boiler design.

Particulate loading was also measured after the dust collector at Sites D, J and K. The other two extensively tested sites, H and I, were not equipped with mechanical dust collectors.

The controlled particulate loading data for sites D, J and K are shown in Figure 4-25. At sites J and K the controlled particulate loading changed very little with grate heat release. Collector efficiencies ranged from 64 to 93%. At Site D, however, the data tend to increase with grate heat release and have considerably more scatter. It is suspected that cyclone tubes were plugging at this site since collector efficiency varied considerably from 16% to 63%.

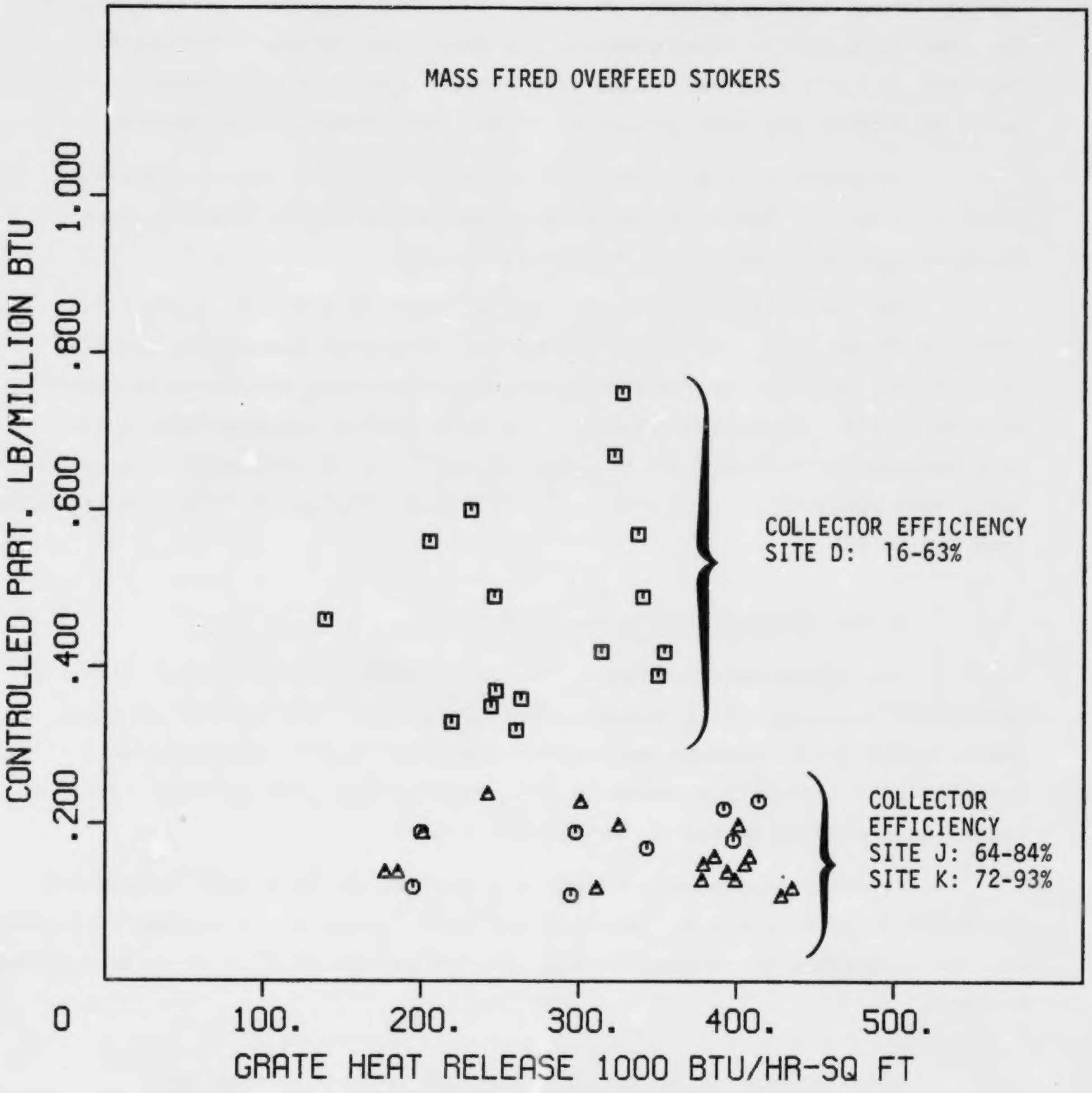
4.3.3 Combustibles in the Flyash vs Heat Release Rate

The combustible content of the uncontrolled flyash did not show a consistent trend with heat release rate. The combusbible content at Sites D, I and K tended to increase as heat release rate increased. Combustibles at Sites H and J tended to decrease with increasing heat release rate. In most cases, data scatter tended to obscure the trend.

Figure 4-26 presents a composite picture of the flyash combustible data for Sites D, H, I, J and K. The data for Site D alone are presented in Figure 4-27 to illustrate the degree of data scatter and the difficulty in determining a trend.

4.3.4 Combustibles in the Bottom Ash vs Heat Release Rate

The combustible content of the bottom ash was even more difficult to relate to heat release rate than the combustible content of the flyash. Figure 4-28 shows a composite picture of the data for Sites D, H, I and J. Except for Site I which had a decreasing trend, the bottom ash combustible data was relatively invariant with load.



□ : SITE D ○ : SITE J △ : SITE K

FIG. 4-25
CONTROLLED PART. VS. GRATE HEAT RELEASE

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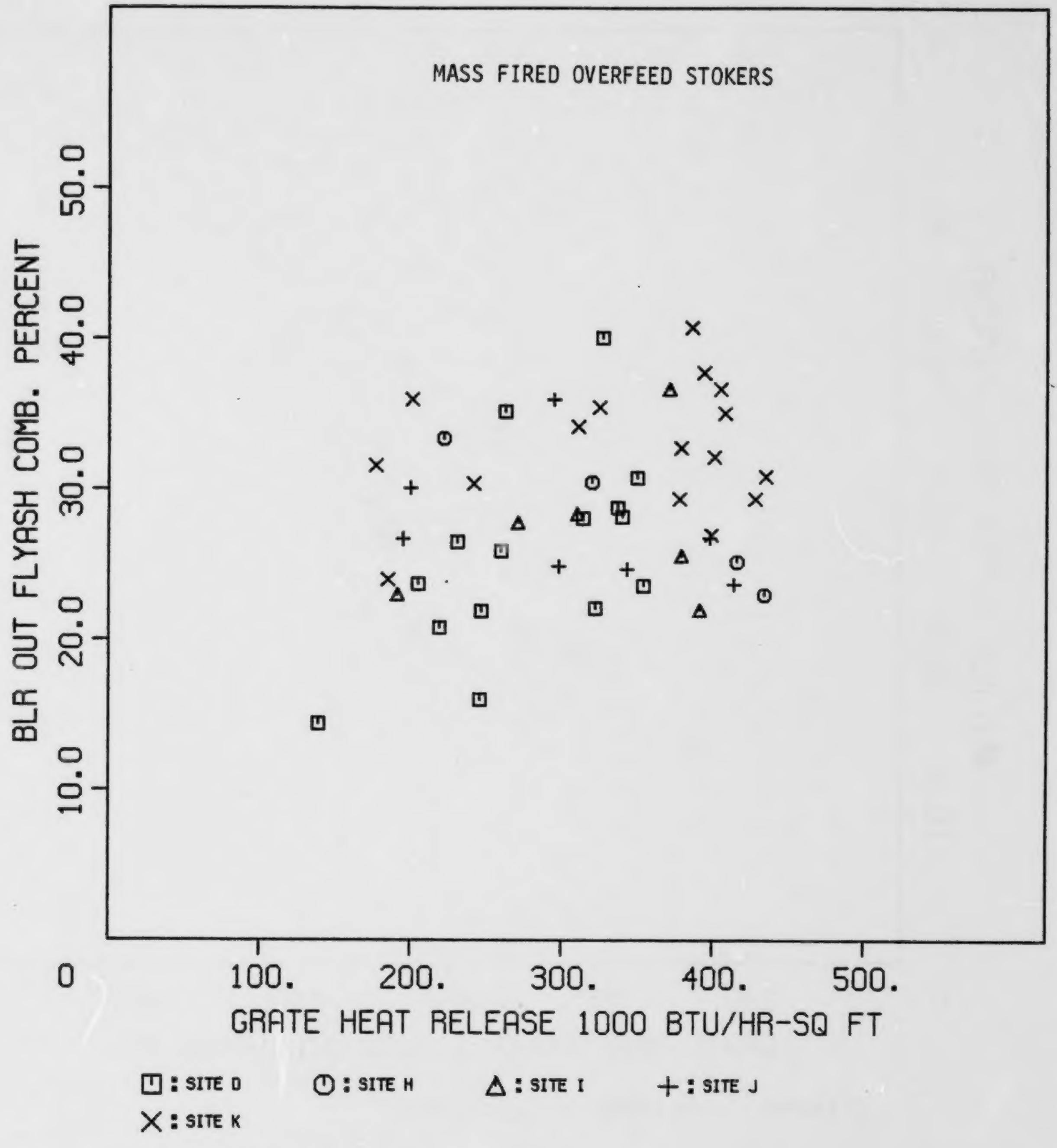

FIG. 4-26
BLR OUT FLYASH COMB. VS. GRATE HEAT RELEASE

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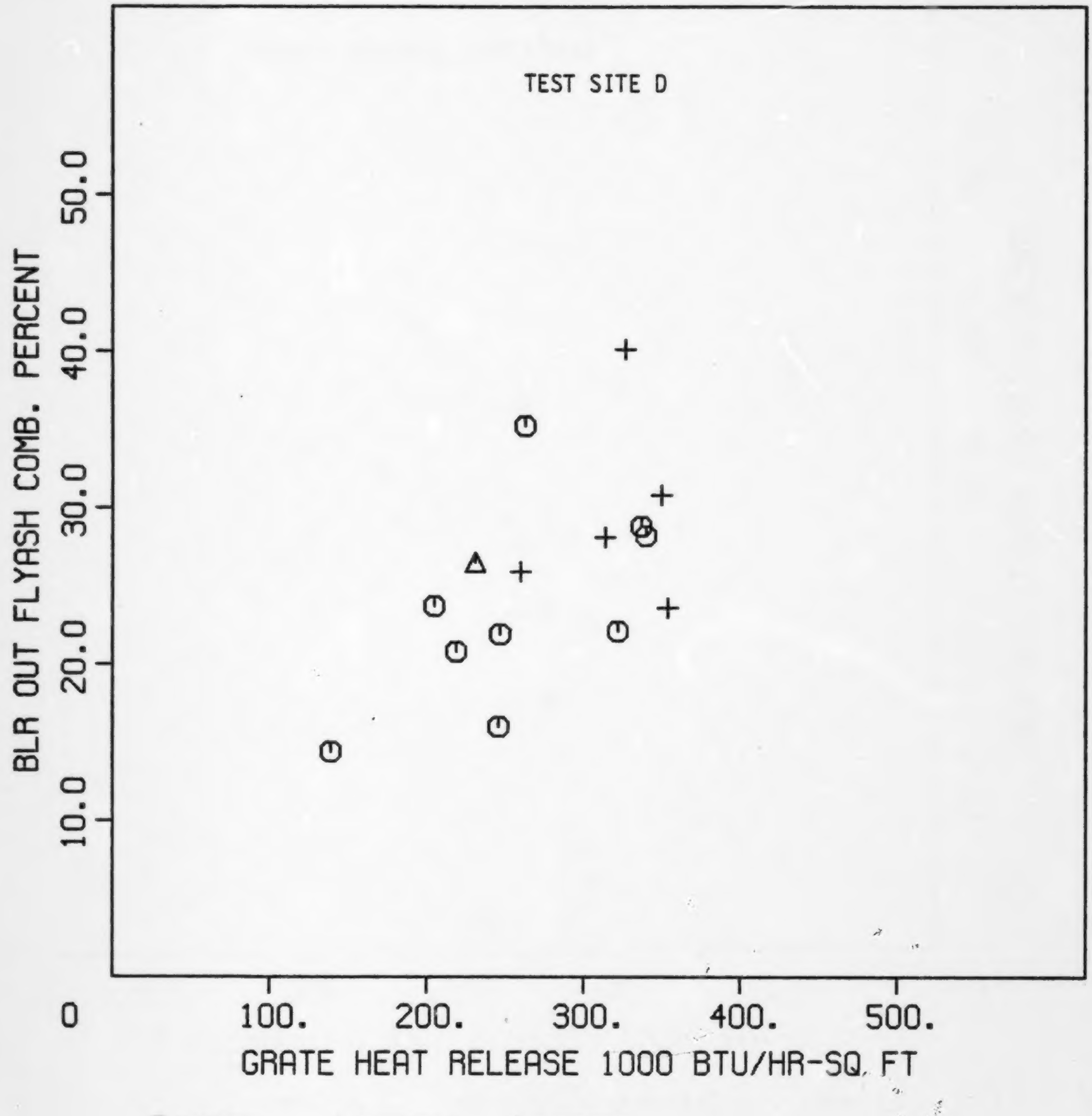

FIG. 4-27
BLR OUT FLYASH COMB. VS. GRATE HEAT RELEASE

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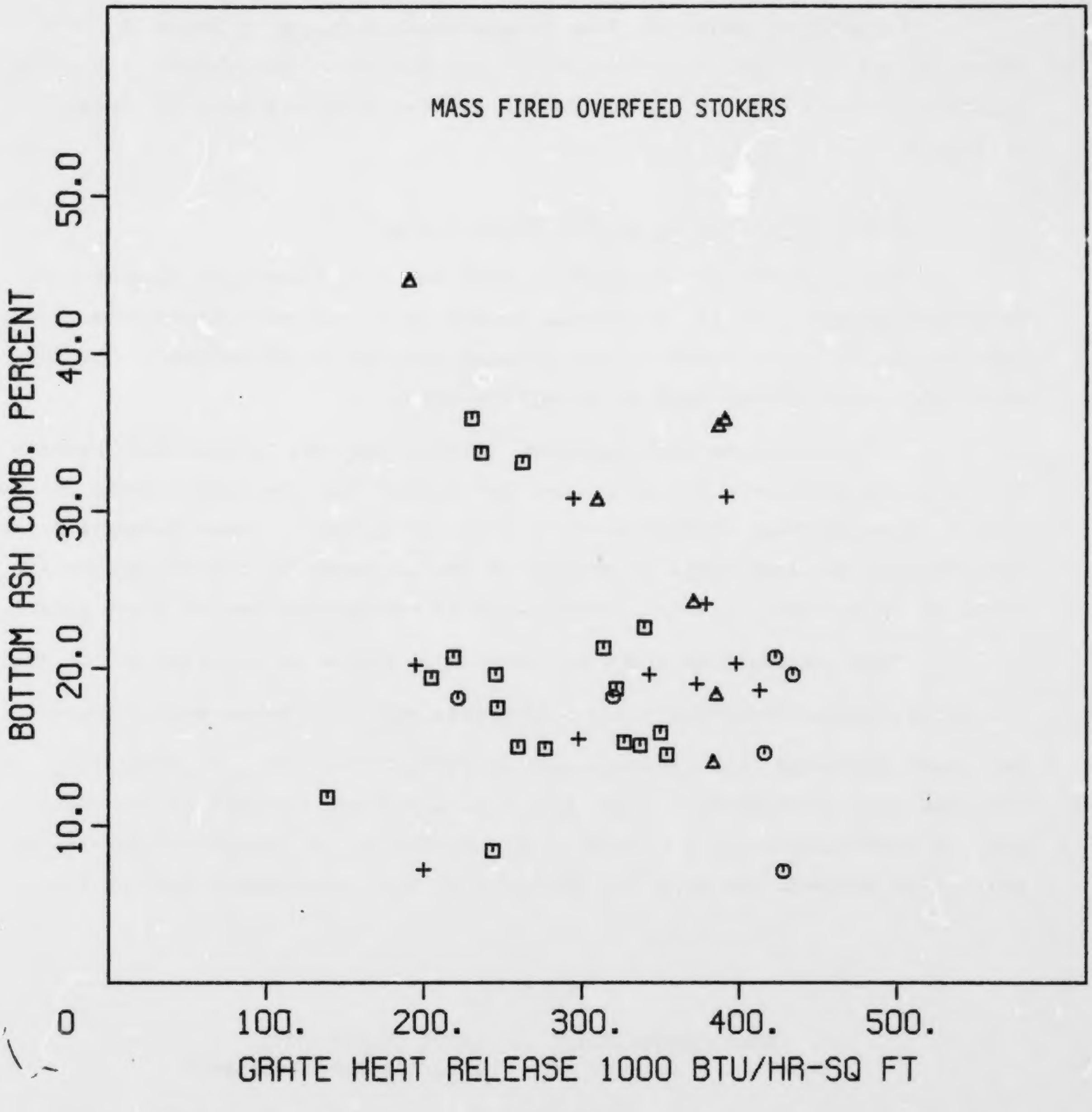

FIG. 4-28
BOTTOM ASH COMB. VS. GRATE HEAT RELEASE

4-15900-554

Figure 4-29 shows the Site K data which exhibits an unusually high degree of scatter. The four highest data points are so unreasonable as to be suspect. Perhaps some of the bottom ash samples at Site K were not representative.

4.3.5 Nitric Oxide vs Heat Release Rate

Nitric oxide is a function of both excess air and heat release rate in stoker boilers. It is, therefore, necessary to sort out the effects of excess air before the effects of heat release rate can be determined. Multiple regression analysis was used to accomplish this.

Two assumptions were required. First, that the relationship between nitric oxide and excess air is linear, and second that the relationship between nitric oxide and heat release rate, or load, is linear. These assumptions are applied over the load range 50 to 100% of design capacity, and the excess air range of 30 to 180%. It would not be wise to extrapolate beyond these limits.

These assumptions allow the data to be fit to an equation of the form:

$$\text{Nitric Oxide, lb}/10^6\text{Btu} = a + b\ (\%\ \text{excess air}) + c\ (\text{grate heat release})$$

The coefficients of this equation were determined for each site separately and are presented in Table 4-13. The Site K data did not fit well to the model and its coefficients are not shown. The coefficient of determination (r^2) is a measure of how well the data fit the equation with 1.0 being a perfect fit.

TABLE 4-13

COEFFICIENTS FOR AN EQUATION OF THE FORM
NOx = a + b (excess air) + c (grate heat release)*

	a	b	c	r^2
Site D	.0615	.00239	.00024	.74
Site H	.0430	.00158	.00061	.52
Site I	.1425	.00161	.00000	.94
Site J	.0770	.00257	.00031	.40

* Grate heat release expressed as 10^3Btu/hr-ft^2 grate area

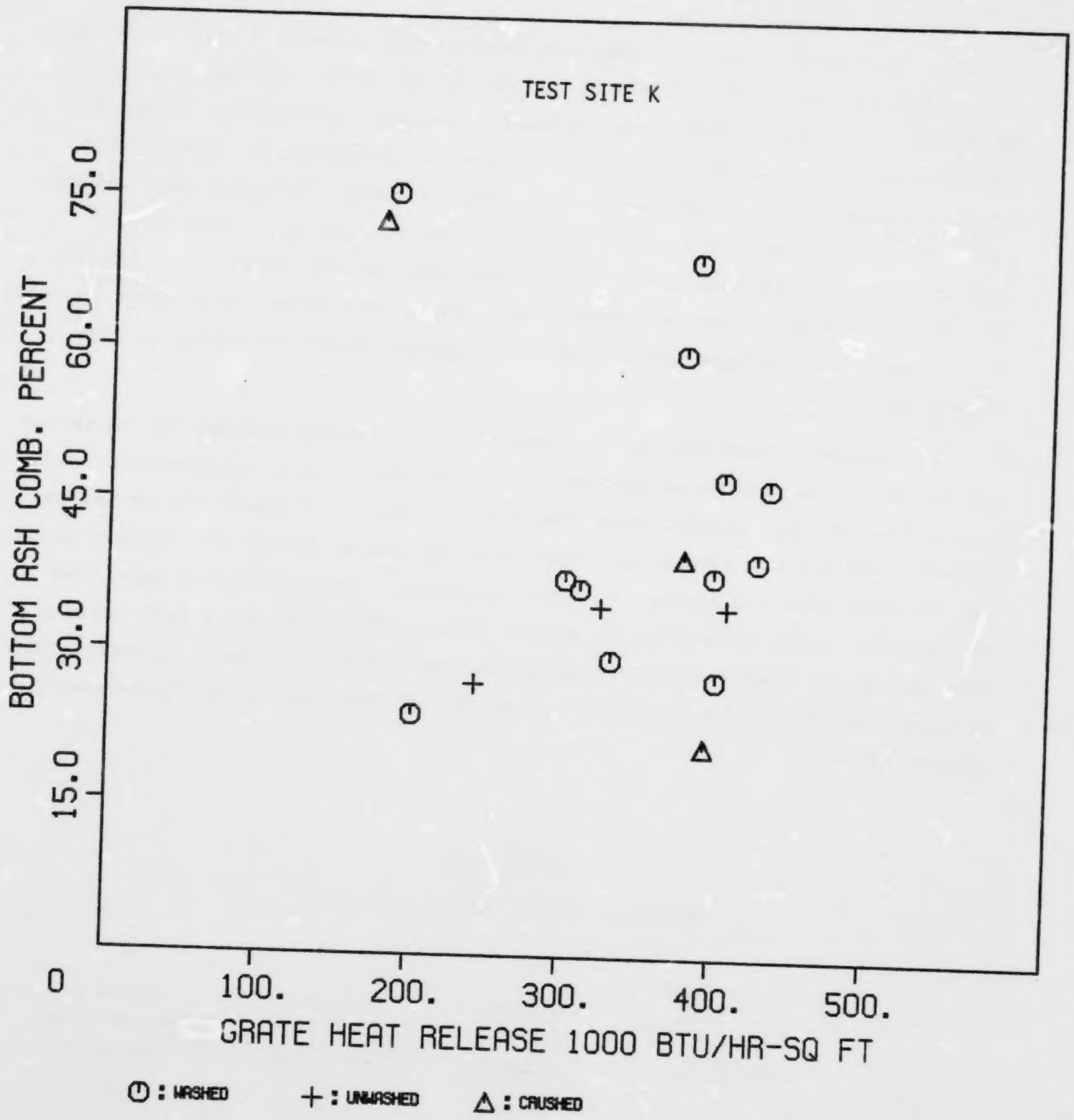

FIG. 4-29

BOTTOM ASH COMB. VS. GRATE HEAT RELEASE

This model indicates that the relationship between nitric oxide and grate heat release ranges from nill to .061 lb NOx/10^6Btu for each 100,000 Btu/hr-ft^2 increase in grate heat release. A visual examination of the data confirms this. For example, the Site I data for Kentucky coal are plotted against excess air in Figure 4-30. The data for three different heat release rates all fall on the same line indicating that NOx was not a function of heat release rate at this site. At the opposite extreme is Site H. The NOx data for Site H are shown in Figure 4-31. These data show a very clear distinction between heat release rates with the greatest spread occurring at high oxygen levels.

Another investigation involved the relationship between NOx emissions and stoker-boiler design parameters. While no unequivocal relationships were found, the NOx test results show (Table 4-14) that the highest NOx emissions, at full load and 50% excess air, were from the stoker having the highest grate heat release rate and highest furnace liberation. The lowest NOx emissions, on the other hand, were from the stoker having the lowest grate heat release rate and second lowest furnace liberation. As Table 4-14 shows, however, this relationship is not clearly borne out by the stokers with intermediate heat release rates.

TABLE 4-14

NITRIC OXIDE VS DESIGN VARIABLES

	Nitric Oxide @ Full Load & 50% Excess Air lb/10^6Btu	Steaming Capacity lb/hr	Furnace Liberation 10^3Btu/hr-ft^3	Grate Heat Release 10^3Btu/hr-ft^2
Site H	.38	45,000	32.3	425
Site J	.33	70,000	21.0	395
Site K	.31	50,000	24.9	406
Site D	.27	90,000	29.3	401
Site I	.22	70,000	24.4	377

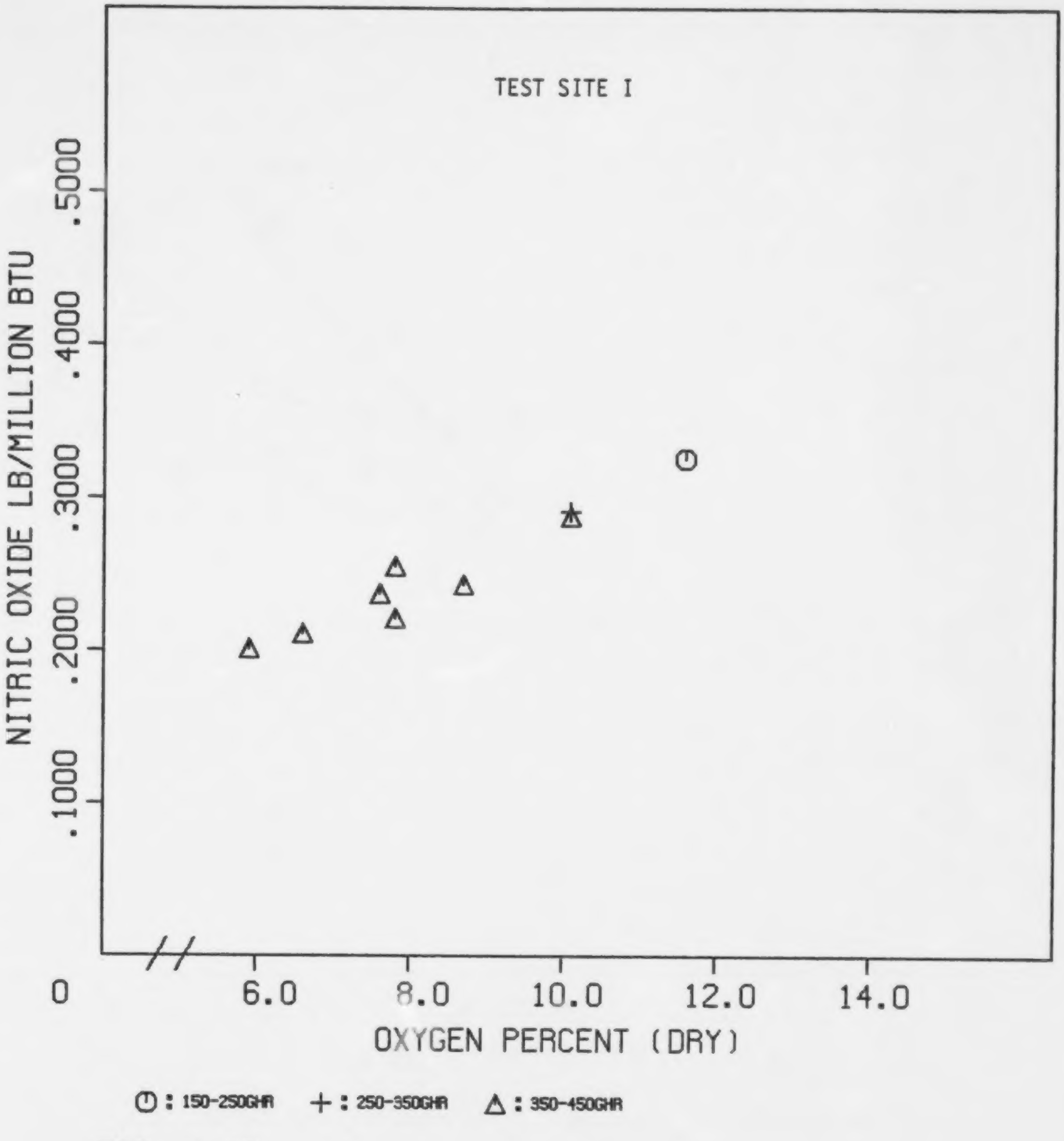

FIG. 4-30
NITRIC OXIDE VS. OXYGEN

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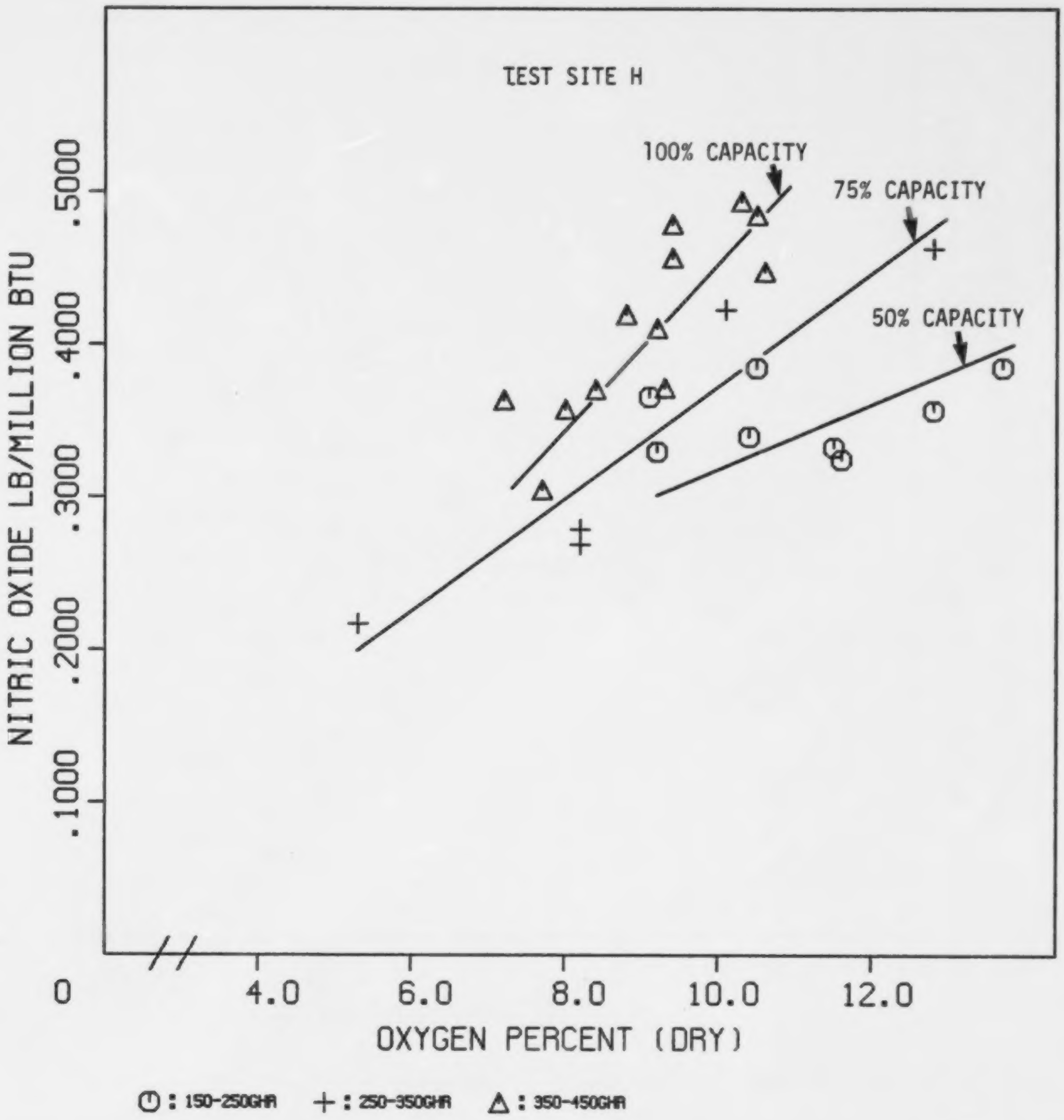

FIG. 4-31
NITRIC OXIDE VS. OXYGEN

4.3.6 Carbon Monoxide vs Heat Release Rate

Carbon monoxide emissions were measured at Test Sites D, H and K. The carbon monoxide analyzer was out of service during testing at Sites I and J.

At the three former sites the carbon monoxide concentration could be maintained below 400 ppm over the entire load range. When carbon monoxide exceeded 400 ppm, it generally occurred at the higher loads and was attributed to low excess air or insufficient overfire air.

A composite plot of all the carbon monoxide data for Sites D, H and K is shown in Figure 4-32.

4.3.7 Unburned Hydrocarbons vs Heat Release Rate

Unburned hydrocarbons were measured at Sites H and J. In both cases, hydrocarbons tended to decrease as heat release rate increased. A composite plot of the data from both sites is shown in Figure 4-33.

4.3.8 Boiler Efficiency vs Heat Release Rate

The boiler efficiency trends with heat release rate are shown in Figure 4-34. Site K has the most unusual trend. At Site K the boiler efficiency dropped off rapidly at reduced loads due to increased dry gas heat losses. The excess air profiles illustrated earlier in Figure 4-19 help explain this drop. In this figure, Site K is seen to have the highest excess air of all the stokers at low loads.

Sites H and I, which have the lowest boiler efficiencies at high loads, were not equipped with economizers, while Sites D, J and K were.

4.4 RESPONSE TO EXCESS AIR

This section discusses the influence of excess air on the emissions and efficiency of five mass fired overfeed stokers. As with spreader stokers, excess air operating level was directly related to boiler load. The variation of excess air at constant load was often very small, making it difficult to determine the influence of this variable on stoker emissions and efficiency. The following are the results of this study.

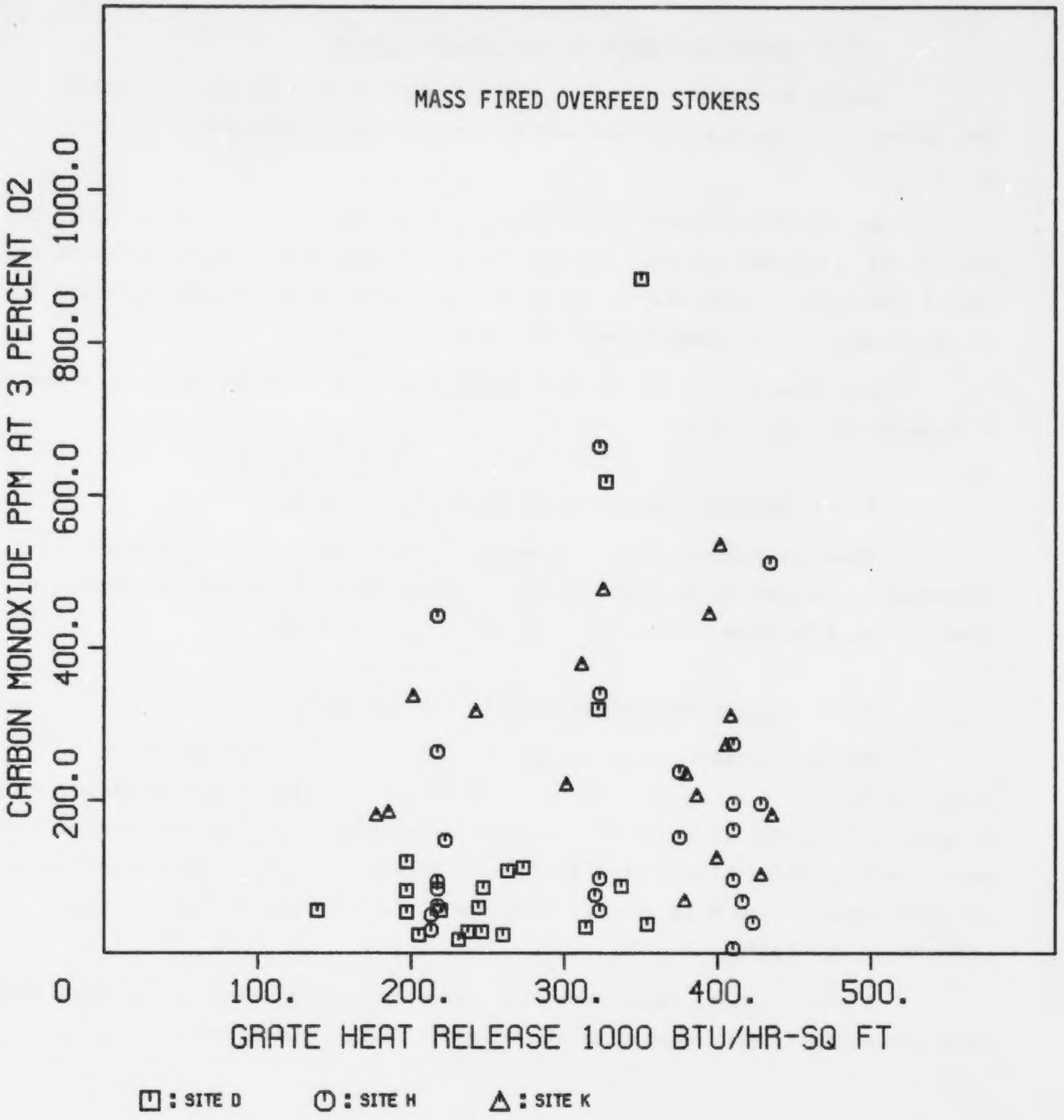

FIG. 4-32
CARBON MONOXIDE VS. GRATE HEAT RELEASE

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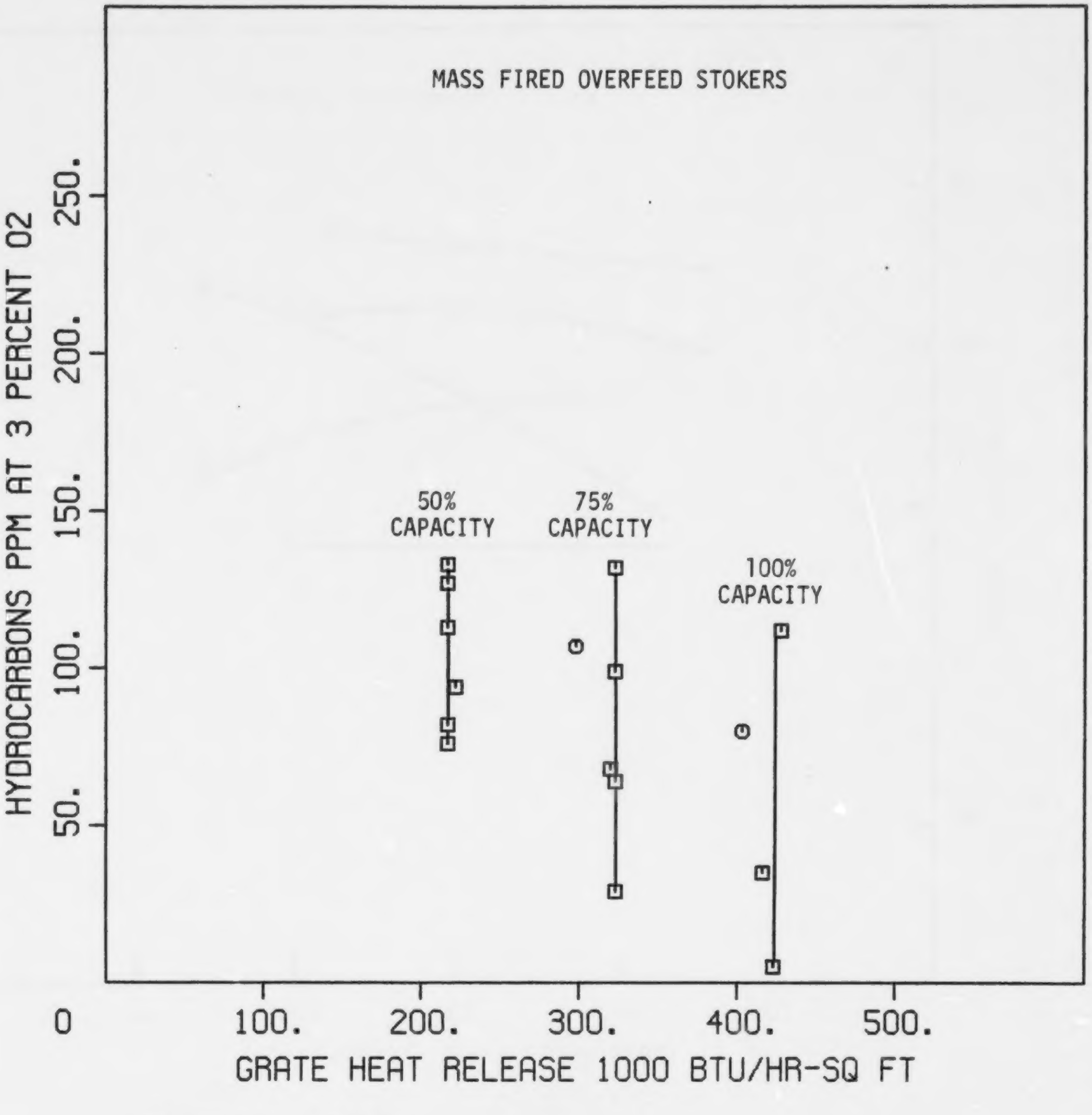

FIG. 4-33
HYDROCARBONS VS. GRATE HEAT RELEASE

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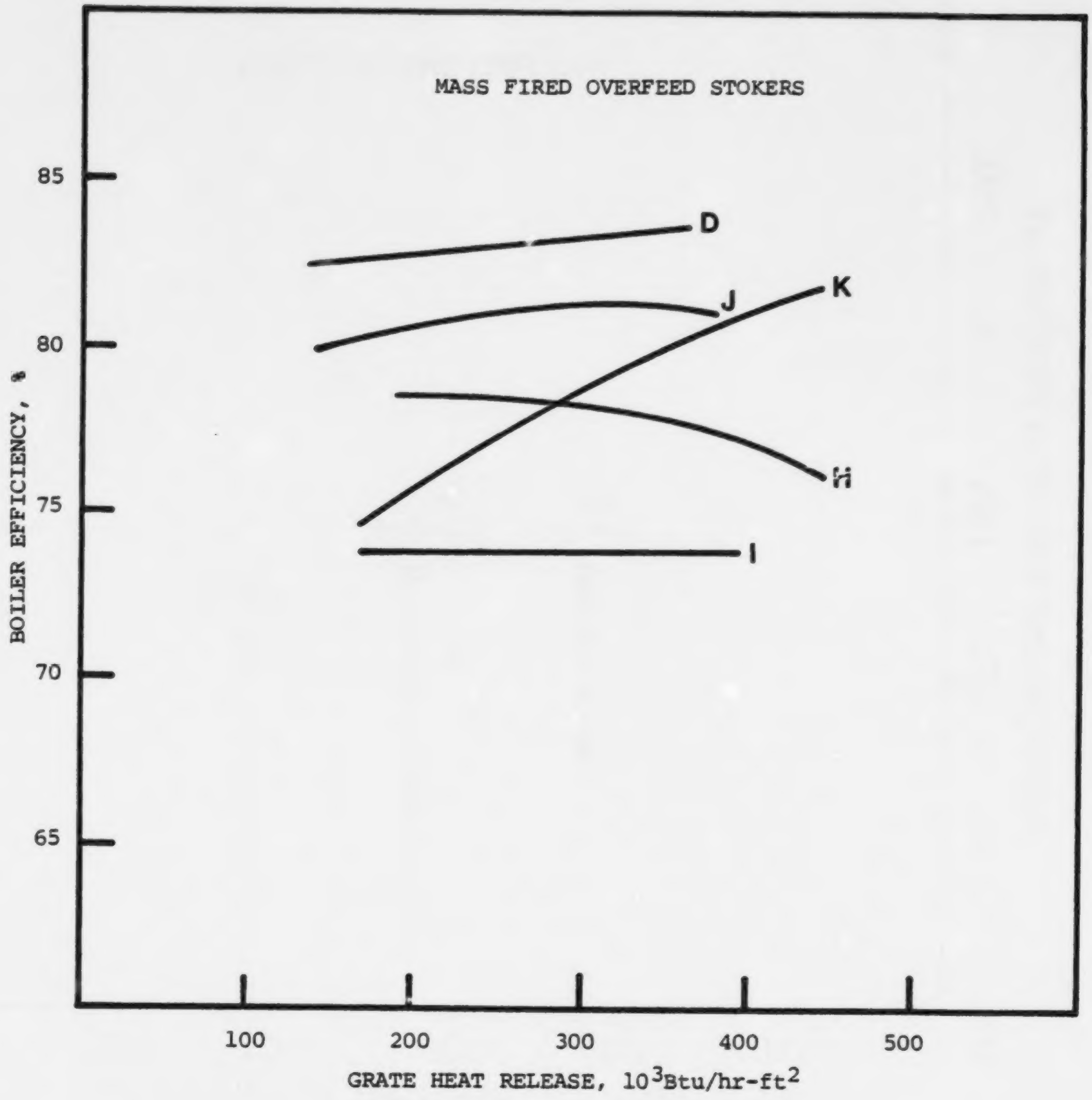


Figure 4-34. Boiler Efficiency as a Function of Grate Heat Release for Five Mass Fired Overfeed Stokers.

4.4.1 Particulate Loading vs Excess Air

No correlation was found between uncontrolled particulate loading and excess air in mass fired overfeed stokers. However, the data base is small and any correlation which may exist could be disguised by one or more uncontrolled variable.

At each site there were at least two tests run at different excess air levels in which the controlled variables of load, overfire air, and coal source were constants. These are listed in Table 4-15.

TABLE 4-15

UNCONTROLLED PARTICULATE LOADING VS EXCESS AIR

	% Excess Air	% Load	Overfire Air "H_2O	% Coal Ash	% Fines < ¼"	Particulate Loading $lb/10^6Btu$
Site D	57	86	10.0	8.47	5.5	0.83
	64	87	10.0	9.14	9.0	1.11
Site H	76	99	11.7	8.73	23.5	1.23
	97	97	11.2	12.34	23.2	0.90
Site I	43	100	10.8	10.37	23.7	0.90
	62	103	10.5	9.15	21.8	0.99
Site J	56	103	7.8	10.22	37.0	1.44
	68	97	7.7	8.23	10.9	0.98
Site K	40	102	2.5	3.51	20.9	0.57
	51	96	2.6	3.44	16.1	0.75
	59	100	2.5	3.32	21.5	0.75
	67	97	2.5	5.55	21.7	1.24

In three of the five data sets the particulate loading increased with excess air, while in the remaining two cases particulate loading decreased. It is also noted that coal fines may have influenced the results at Site D and J.

Multiple regression analysis was applied to the mass fired overfeed stoker data as an alternate method of sorting out the relationships between uncontrolled particulate loading, percent load and excess air. The results were just as irregular as those for spreader stokers. However, because the data base is small, the results of this method may not be valid and are, therefore, not included.

4.4.2 Combustibles in the Ash vs Excess Air

The percentage of combustible material in the flyash and in the bottom ash did not correlate with excess air. The same examples cited for particulate loading in Table 4-15 are presented for combustible content in Table 4-16.

TABLE 4-16

COMBUSTIBLES IN THE ASH VS EXCESS AIR
FOR MASS FIRED OVERFEED STOKERS

	Excess Air	% Combustibles in Flyash	% Combustibles in Bottom Ash
Site D	57	28.8	15.1
	64	22.1	18.7
Site H	76	23.0	20.7
	97	25.2	14.6
Site I	43	25.6	ND*
	62	22.0	35.9
Site J	56	23.7	ND*
	68	ND*	30.9
Site K	40	30.9	46.8
	51	40.8	69.1
	59	36.7	47.6
	67	32.2	27.6

*ND = No Data

4.4.3 Nitric Oxide vs Excess Air

Nitric oxide increased with excess air in a well defined and consistent manner. The rate of increase averaged .0216 lb NOx/10^6Btu per 10% increase in excess air at constant load. The relationships, presented in Table 4-17, were determined by multiple regression analysis for Sites D, H, I and J, and by linear regression on the full load data for Site K. The Site K data did not fit the model when all loads were considered, but the full load data correlated with excess air, which was consistent with that of the other sites in this class.

TABLE 4-17

NITRIC OXIDE VS EXCESS AIR
AT CONSTANT LOAD

	lb NOx/10^6Btu per 10% Excess Air
Site D	.0239
Site H	.0158
Site I	.0161
Site J	.0257
Site K	.0265

These data are presented graphically in Figure 4-35. This figure gives the magnitude as well as the slope of the data for the case of full load on the boiler.

4.4.4 Carbon Monoxide vs Excess Air

Carbon monoxide emissions rose sharply as excess air dropped below about 60% at Sites D and H, and rose more gradually as excess air increased above 120% at Site H.

The Site K data show more scatter, probably because overfire air was a major factor at this site. When only the high overfire air tests at Site K are considered, the data fall in line with that measured at Sites D and H.

The data for Sites D, H and K are presented in Figure 4-36, and the general trend is outlined. Carbon monoxide was not measured at Sites I and J because the CO analyzer was out of service at these two sites.

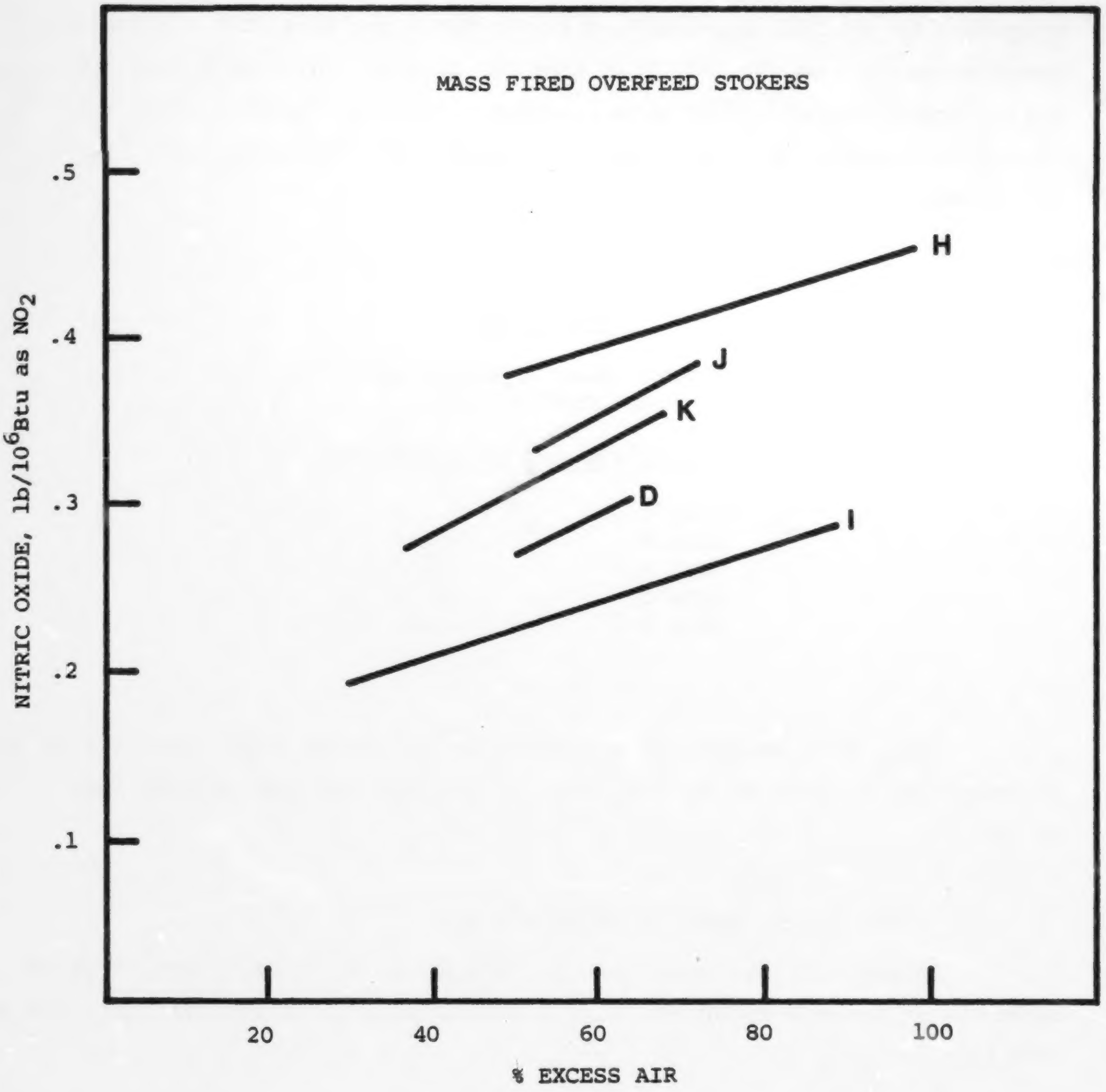


Figure 4-35. The Relationship Between Nitric Oxide and Excess Air at Full Load.

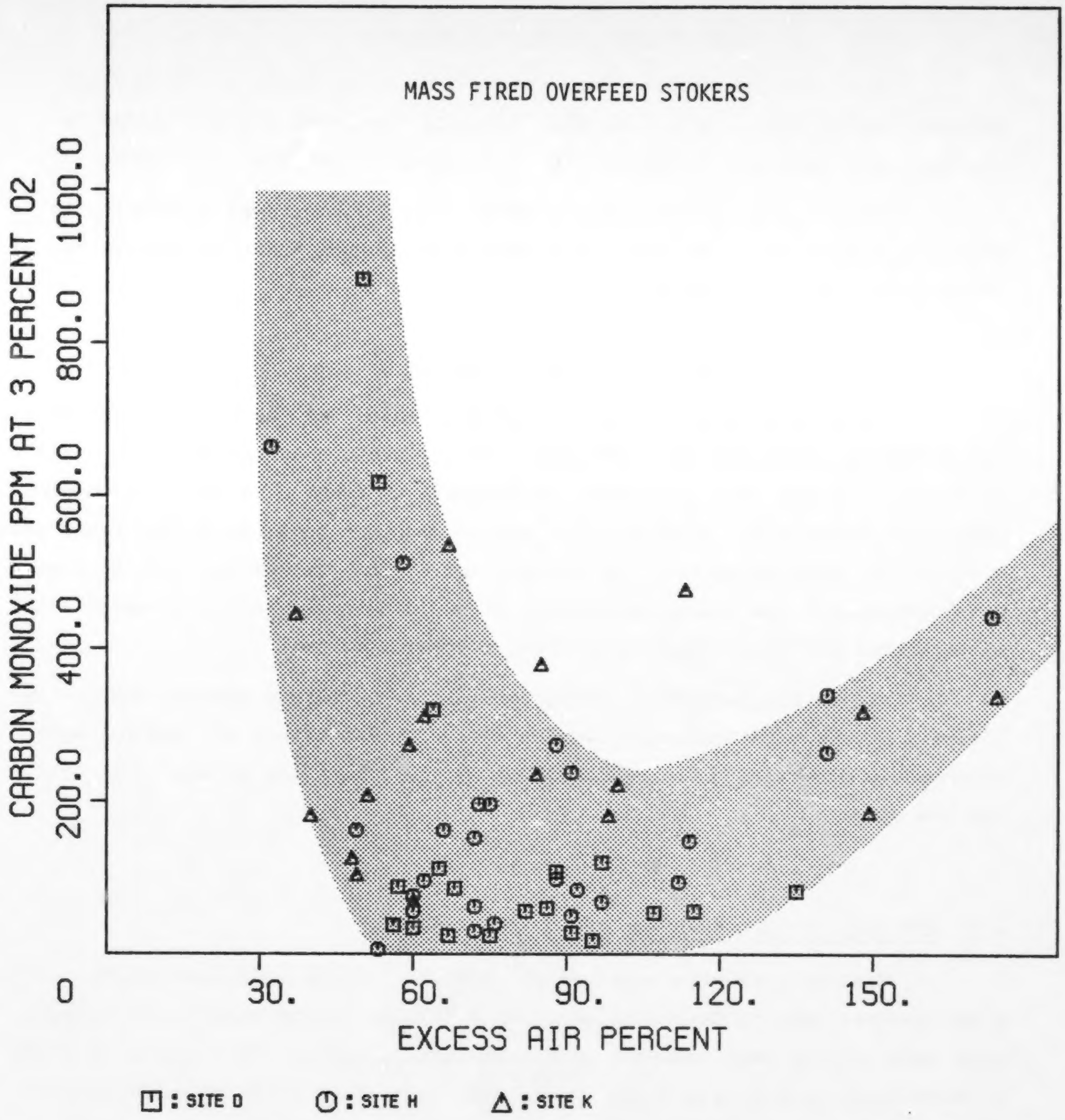


FIG. 4-36
CARBON MONOXIDE VS. EXCESS AIR

4.4.5 Unburned Hydrocarbons vs Excess Air

Unburned hydrocarbons were measured at Sites H and J. Unlike the spreader stoker data, the hydrocarbon data for these two stokers tended to increase as excess air increased. This trend is illustrated in Figure 4-37.

The unburned hydrocarbons at Test Site H also showed a correlation with carbon monoxide. As shown in Figure 4-38, carbon monoxide appears to increase exponentially as hydrocarbons increase.

4.4.6 Boiler Efficiency vs Excess Air

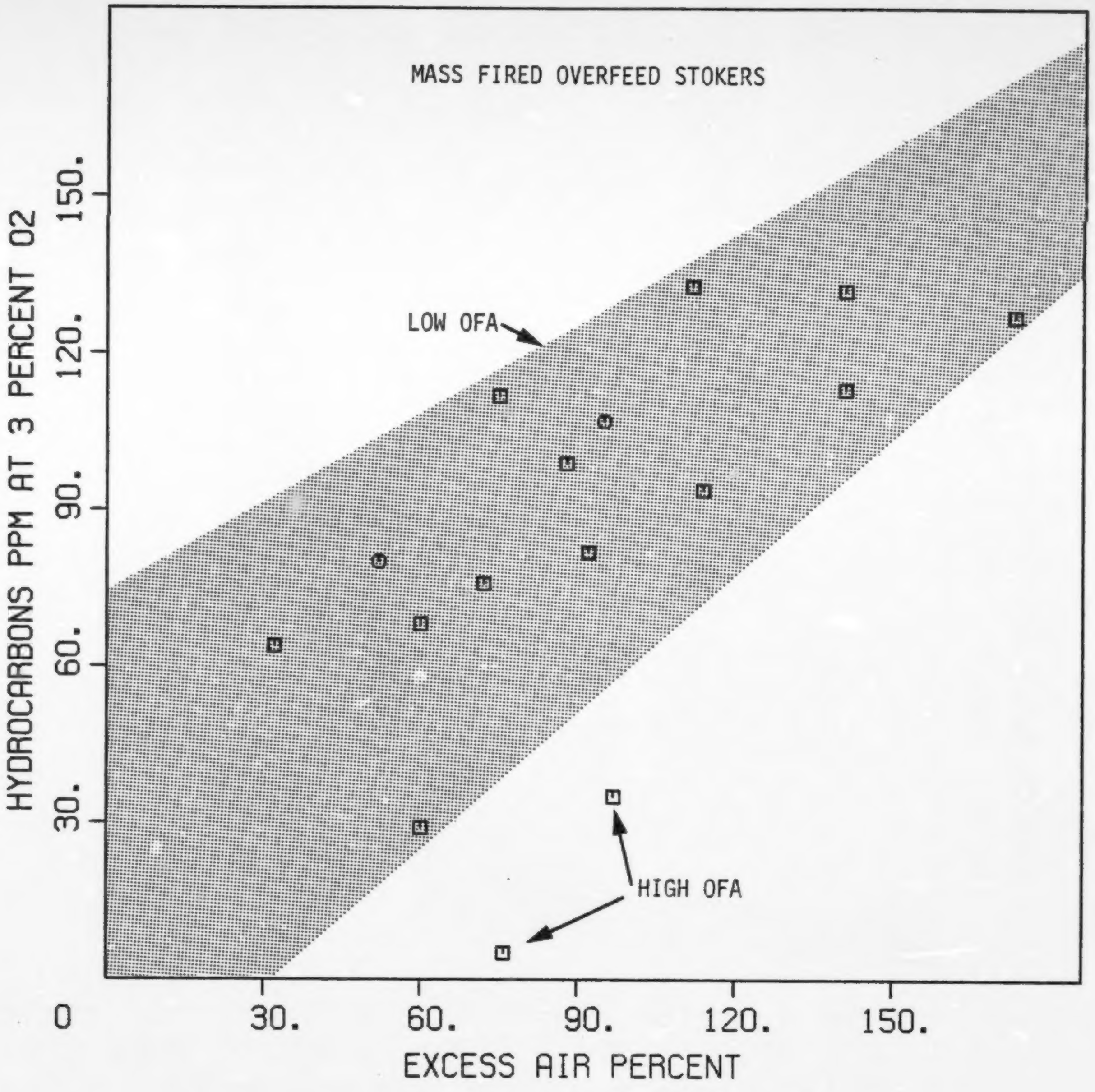
The relationship between boiler efficiency and the variable excess air was determined visually for each site. Boiler efficiency trends are plotted in Figure 4-39 and show efficiency to decrease by about 0.5% for each 10% increase in excess air. This is not based on constant load but rather takes into account all tests conducted. At Sites H and I, the boilers were not equipped with economizers and boiler efficiency at a constant excess air is about 4 to 6% less than the other three mass fired overfeed stokers.

Excess air influences boiler efficiency primarily because the dry gas losses increase with increasing excess air. The additional air absorbs heat which would otherwise have been absorbed by the boiler and carries that heat out the stack.

4.5 RESPONSE TO COAL ANALYSIS AND SIZING

Coal samples were obtained and analyzed during each test which included a particulate loading determination. As a result, it was possible to compare test results with coal analysis on a test-by-test basis. At Sites D, I, J and K, more than one coal was fired in the same unit, thus allowing a comparison of emissions from different coals. This section examines the effect which varying coal properties had on stoker emissions.

The coal properties are summarized in Tables 4-18 through 4-23. Table 4-18 identifies the coals and gives the ASTM classification based on the average of samples obtained during these tests. The following five tables include proximate analysis, ultimate analysis, ash fusion temperature, mineral analysis



H : SITE H   J : SITE J

FIG. 4-37
HYDROCARBONS VS. EXCESS AIR

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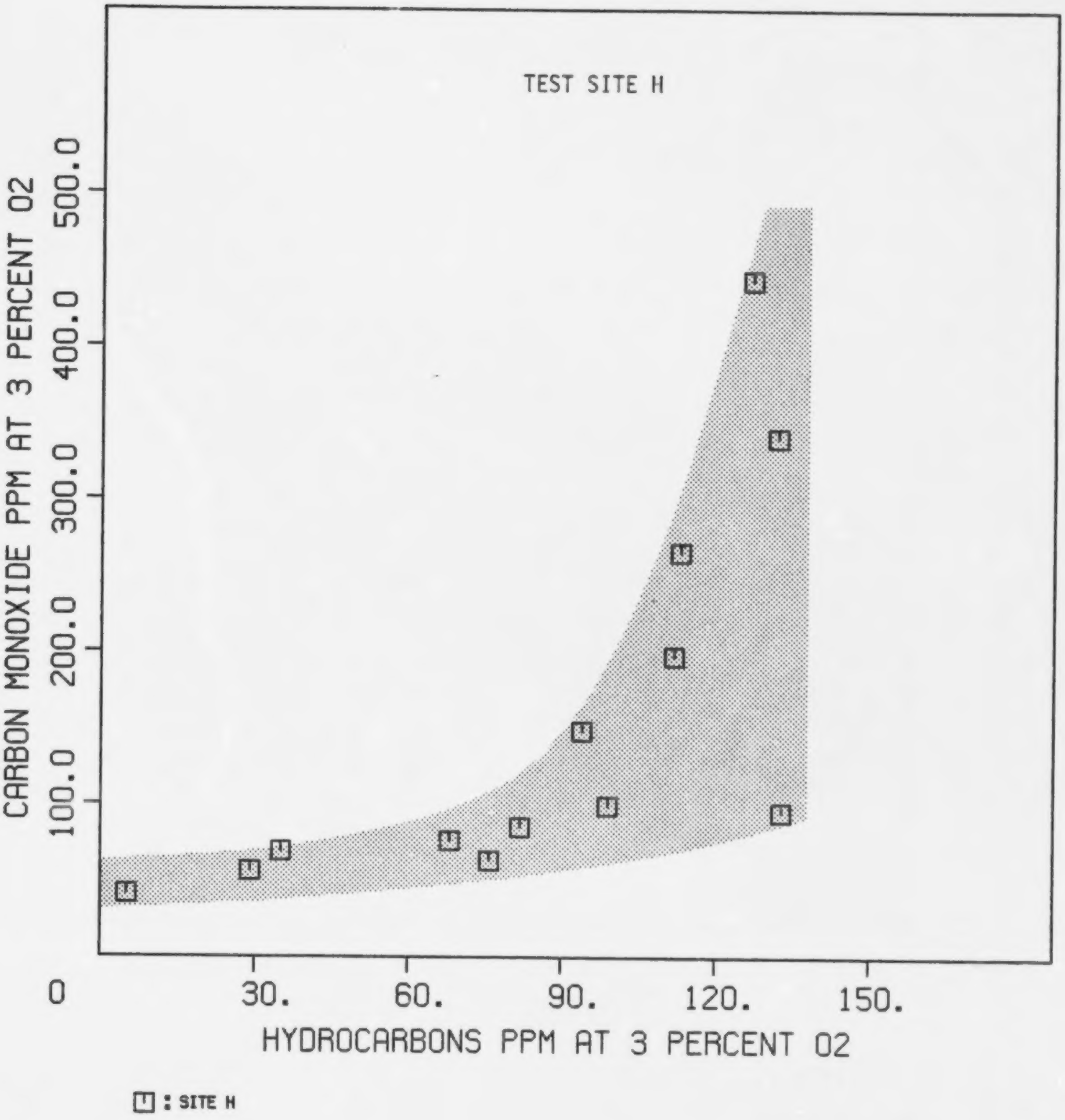

FIG. 4-38
CARBON MONOXIDE VS. HYDROCARBONS

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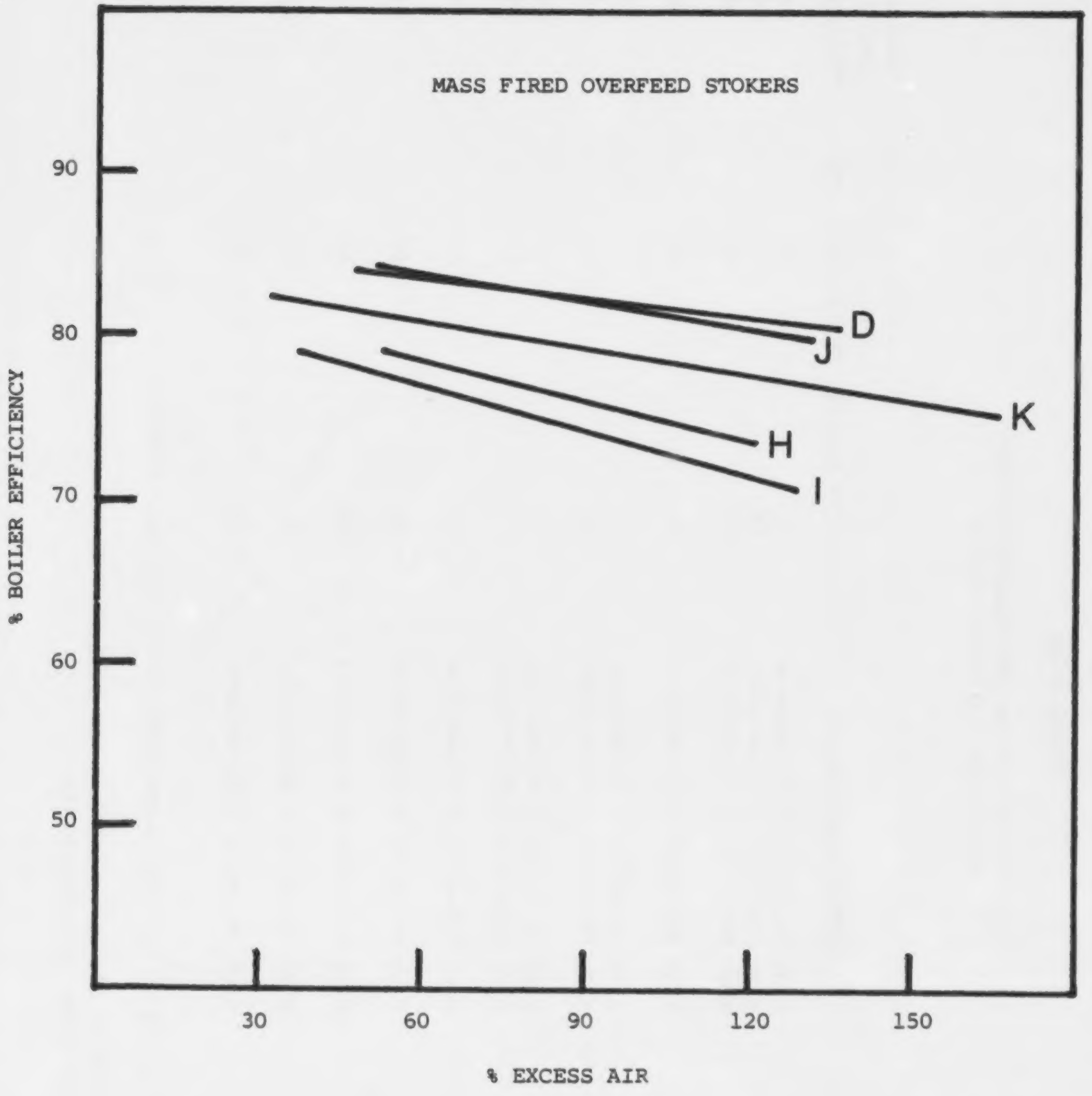

Figure 4-39. Relationship Between Boiler Efficiency and Excess Air.

TABLE 4-18

COAL IDENTIFICATION AND CLASSIFICATION*
MASS FIRED OVERFEED STOKERS

	Coal	Identification**	ASTM Classification	Fixed Carbon (Dry, Mineral-Matter-Free Basis)	Volatile Matter (Dry, Mineral-Matter-Free Basis)	Calorific Value (Moist, Mineral-Matter-Free Basis)
Site D	1	Century	High Volatile A Bituminous	56	44	14,440
	2	Perfect 8	High Volatile A Bituminous	59	41	14,590
	3	Victoria	High Volatile A Bituminous	59	41	14,490
Site H	1	Sands Hill	High Volatile C Bituminous	57	43	12,630
Site I	1	Ohio (C&W)	High Volatile A Bituminous	57	43	14,430
	2	Kentucky (Spurlock)	High Volatile A Bituminous	58	42	14,840
Site J	1	Ohio (C&W)	High Volatile A Bituminous	58	42	14,390
	2	Kentucky (Spurlock)	High Volatile A Bituminous	58	42	14,700
Site K	1	Washed (Brilliant)	High Volatile B Bituminous	59	41	13,890
	2	Unwashed (Brilliant)	High Volatile B Bituminous	60	40	13,840
	3	Washed & Crushed (Brilliant)	High Volatile B Bituminous	59	41	13,720
Site L2	1	C&C	High Volatile A Bituminous	64	36	15,300
Site L4	1	Consolidation	High Volatile A Bituminous	60	40	14,920

* Classification of coals is by rank (ASTM D388) using the Parr Formulas.

** Coals are identified by the names used in the published Site reports. Alternate names are given in parenthesis.

TABLE 4-19

PROXIMATE COAL ANALYSIS
MASS FIRED OVERFEED STOKERS

	Coal	Weight Percent as-Fired Moisture	Ash	Volatile	Fixed Carbon	Btu/lb	% Sulfur
Site D	1	3.23	8.71	39.17	48.89	13003	2.60
	2	2.68	5.86	38.44	53.02	13629	1.23
	3	3.11	6.72	37.25	52.94	13405	1.11
Site H	1	11.56	8.62	35.16	44.66	11417	1.88
Site I	1	3.28	9.57	38.02	49.05	12858	2.77
	2	2.26	6.04	38.79	52.92	13823	1.49
Site J	1	3.59	7.85	37.83	50.73	13117	1.70
	2	2.24	6.57	39.09	52.10	13607	1.58
Site K	1	6.49	4.14	37.46	51.91	13237	1.11
	2	6.19	10.24	33.69	49.88	12280	1.01
	3	7.35	4.68	36.72	51.25	12994	1.31
Site L2	1	1.60	13.00	32.70	53.60	13100	1.40
Site L4	1	1.60	8.50	37.50	53.00	13500	1.60

TABLE 4-20

ULTIMATE COAL ANALYSIS
MASS FIRED OVERFEED STOKERS

		Weight Percentage as-Fired							
	Coal	Moisture	Carbon	Hydrogen	Nitrogen	Chlorine	Sulfur	Ash	Oxygen
Site D	1	3.23	72.07	5.01	1.23	0.12	2.60	8.71	7.03
	2	2.68	76.08	5.15	1.33	0.13	1.23	5.86	7.54
	3	3.11	74.96	5.00	1.30	0.07	1.11	6.72	7.76
Site H	1	11.76	63.73	4.36	1.08	0.07	1.72	8.93	8.87
Site I	1	3.02	71.46	4.93	1.51	0.28	2.42	9.22	7.17
	2	2.24	76.83	5.24	1.47	0.13	1.40	5.71	6.97
Site J	1	3.05	74.74	5.13	1.66	0.19	1.75	7.05	6.43
	2	1.96	76.77	5.09	1.23	0.13	1.43	7.25	6.14
Site K	1	6.80	73.85	5.00	1.55	0.07	1.39	3.91	7.43
	2	4.76	72.21	4.63	1.44	0.05	1.10	7.98	7.78
	3	5.84	74.25	4.97	1.42	0.06	0.94	4.15	8.37

TABLE 4-21

FUSION TEMPERATURE OF THE ASH
REDUCING ATMOSPHERE
MASS FIRED OVERFEED STOKERS

	Coal	Initial Deformation	Softening H=W	Softening H=½W	Fluid
Site D	1	2050 °F	2320 °F	2380 °F	2520 °F
	2	2680	2700+	2700+	2700+
	3	2590	2700+	2700+	2700+
Site H	1	2205	2363	2403	2598
Site I	1	2060	2195	2335	2465
	2	2070	2230	2390	2555
Site J	1	2100	2250	2400	2535
	2	2205	2335	2465	2580
Site K	1	2100	2280	2310	2600
	2	2110	2470	2510	2700+
	3	2190	2330	2360	2610
Site L2	1		2650		
Site L4	1		2500		

TABLE 4-22

MINERAL ANALYSIS OF THE ASH
MASS FIRED OVERFEED STOKERS

	Coal	Silica SiO_2	Alumina Al_2O_3	Titania TiO_2	Ferric Oxide FeO_3	Lime CaO	Magnesia MgO	Potassium Oxide K_2O	Sodium Oxide Na_2O	Sulfur Trioxide SO_3	Phosphorus Pentoxide P_2O_5	Undetermined
Site D	1	45.24	23.83	1.18	24.72	1.04	0.62	1.82	0.42	0.62	0.13	0.25
	2	47.07	32.74	1.42	9.24	2.23	1.10	1.99	0.63	1.85	0.32	0.92
	3	50.22	30.63	1.55	9.77	1.90	0.79	1.66	0.48	1.17	0.53	0.92
Site H	1	43.83	25.34	1.09	22.21	1.75	0.67	1.89	0.26	0.35	0.72	1.80
Site I	1	38.94	23.04	1.22	27.22	2.39	0.81	1.93	0.33	1.55	0.34	2.23
	2	43.28	24.44	1.51	18.33	3.22	0.77	1.62	0.85	3.36	0.27	2.38
Site J	1	42.48	26.60	1.29	22.09	2.11	0.83	1.91	0.35	1.43	0.40	0.38
	2	44.08	26.46	1.51	17.80	2.28	0.78	1.78	0.80	1.85	0.31	1.89
Site K	1	38.35	26.25	1.14	21.19	5.59	1.57	1.75	0.25	1.99	0.10	1.82
	2	52.64	24.64	0.88	12.41	2.62	1.32	2.75	0.27	1.63	0.05	0.79
	3	43.86	26.25	1.10	15.86	4.73	1.47	2.15	0.27	3.59	0.05	0.67

TABLE 4-23

AS-FIRED COAL SIZE CONSISTENCY
MASS FIRED OVERFEED STOKERS

		Percent Passing Stated Screen Size				
	Coal	1"	½"	¼"	#8	#16
Site D	1	99	49	9	4	3
	2	96	50	15	6	4
	3	89	40	16	8	5
Site H	1	93	57	26	12	8
Site I	1	85	55	30	14	9
	2	95	51	24	13	9
Site J	1	84	41	18	10	7
	2	94	36	10	5	4
Site K	1	75	37	20	9	5
	2	62	38	25	15	11
	3	95	70	44	22	13

of the ash and coal size consistency. The data base and table number for each analysis are as follows:

Analysis	Data Base	Table No.
Proximate	72 samples	Table 4-19
Ultimate	32 samples	Table 4-20
Ash Fusion	14 samples	Table 4-21
Mineral	14 samples	Table 4-22
Size Consist	72 samples	Table 4-23

4.5.1 Particulate Loading vs Coal Properties

Two coal properties were examined for their relationship to particulate loading. These were coal ash on a mass percent basis, and coal fines as mass percent passing a 1/4 inch screen. Test Site K was the only site where there was enough variation in these variables to cause a change in the particulate loading. Therefore, this discussion will center around the Site K test results. The Test Site K particulate data are summarized in Table 4-24. The particulate data are plotted as a function of boiler load in Figures 4-40 and 4-41.

At Site K, three forms of the same coal were tested. The primary coal was a 1-1/4"x0 washed coal. In one series of tests, unwashed coal from the same mine was tested. The unwashed coal contained clay and other impurities which increased its ash content from 4% to 10%. Apparently, the impurities were of a size to be easily carried over, but at the same time, easily collected by the dust collector. Particulate loading of the unwashed coal was three times greater than that of the washed coal at the boiler outlet. The particulate loading after the dust collector was only slightly greater for the unwashed coal.

In another series of tests, the washed coal was put through a crusher which reduced its top size from 1-1/4" down to 3/4" and at the same time increased its fines (<1/4") from about 20% to about 40%+. The results of these tests show that particulate loading increased 15% at low load, 51% at medium load, and 58% at full load. This corresponds to a .23 lb/10^6Btu particulate increase for each 10% fines increase at full load. At the same time, collector efficiency increased so that no change was seen after the dust collector.

TABLE 4-24

PARTICULATE LOADING VS COAL PROPERTIES
TEST SITE K

	50% Capacity			75% Capacity			100% Capacity		
	Washed	Unwashed	Crushed	Washed	Unwashed	Crushed	Washed	Unwashed	Crushed
Coal Ash, %	5.18	8.40	5.28	4.24	8.35	4.57	4.16	13.96	4.19
Coal Fines, % < ¼"	25	23	42	17	32	54	20	22	39
Excess Air, %	162	148	98	93	113	84	53	62	37
Uncontrolled Particulate, lb/10^6Btu	.61	1.25	.70	.75	2.06	1.13	.78	2.20	1.23
Controlled Particulate, lb/10^6Btu	.17	.24	.14	.17	.20	.15	.14	.16	.14
Dust Collector Efficiency, %	72.0	80.9	79.4	77.5	90.4	87.0	81.2	92.7	88.6

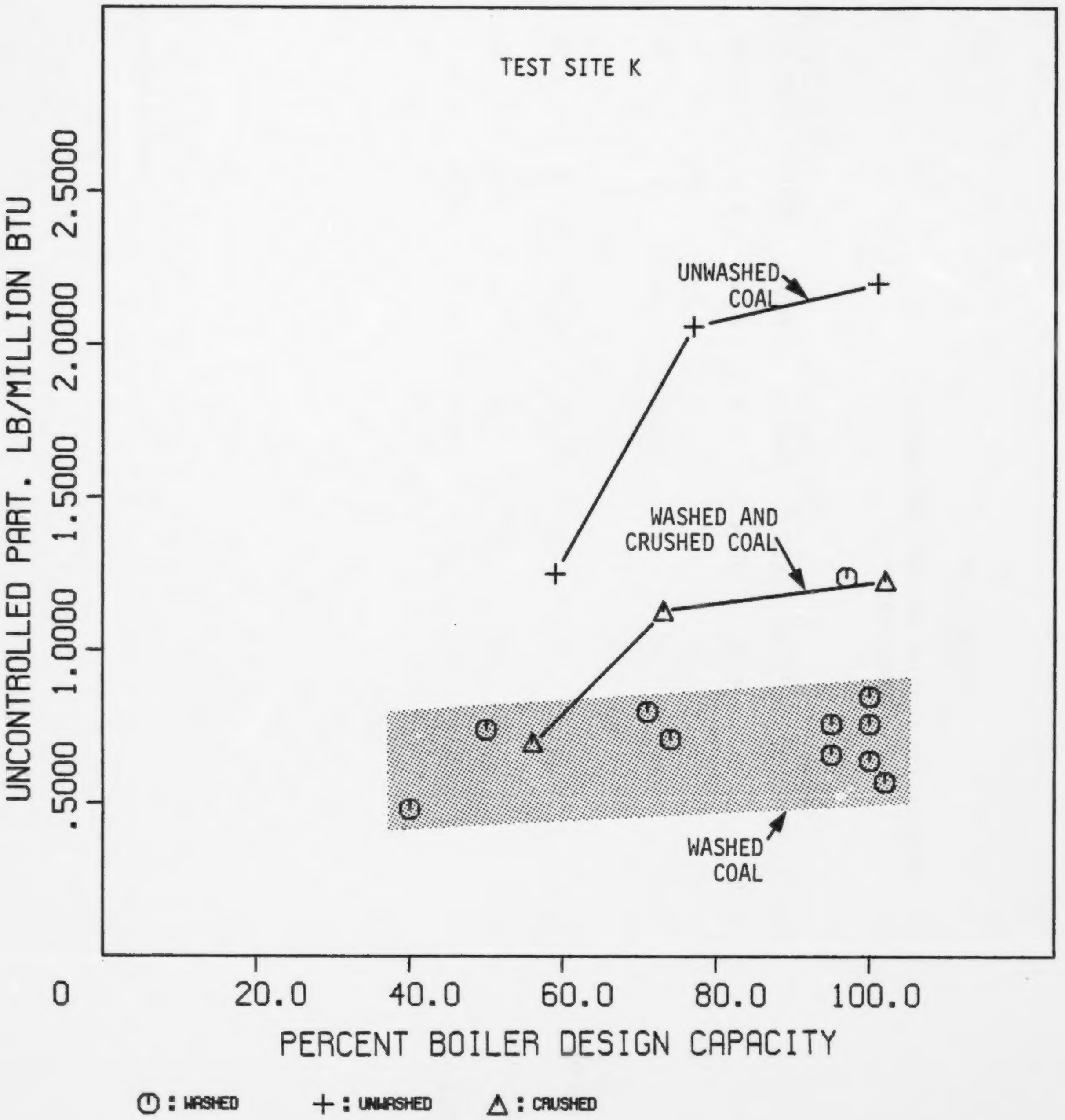

FIG. 4-40
UNCONTROLLED PART. VS. PERCENT DESIGN CAPACITY

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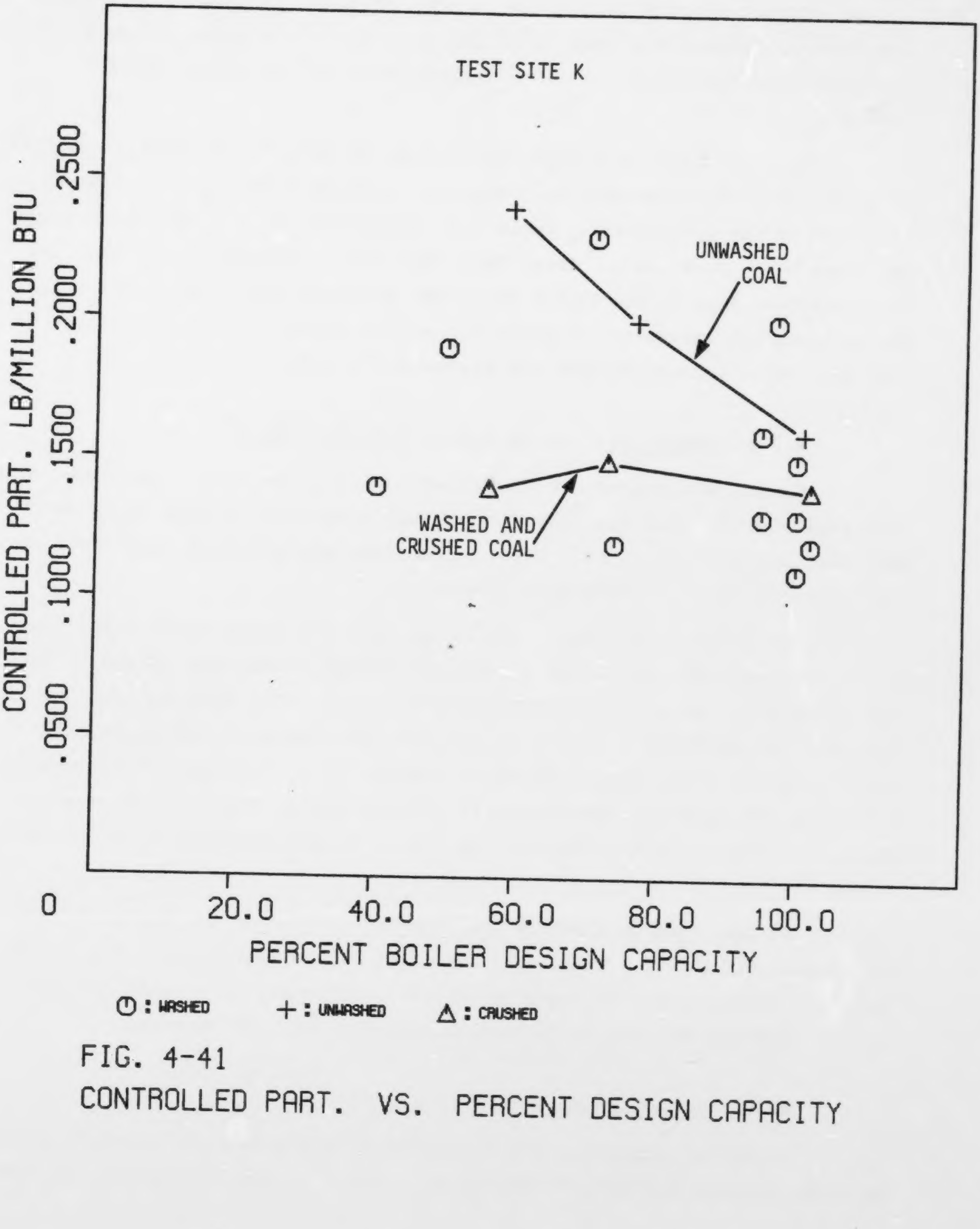

FIG. 4-41
CONTROLLED PART. VS. PERCENT DESIGN CAPACITY

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Mechanical dust collectors are seen as great normalizers to particulate loading. More often than not during this program, changes to the particulate loading at the boiler outlet were diminished or lost after the dust collector.

Coal ash makes up a major portion of the particulate material emitted from mass fired overfeed stokers. However, combustible material also makes up a portion of the particulate. Table 4-25 summarizes the coal ash disposition for Sites D, H, I, J and K. These data show that an average 13% of the coal's ash is carried over in the flyash while the remaining 87% stays on the grate. The as-found ash carryover (includes combustible material) equalled 19% of the coal ash, while bottom ash mass was equivalent to 128% of the coal ash.

4.5.2 Combustibles in the Ash vs Coal Properties

Combustible content of the boiler outlet flyash and of the bottom ash were evaluated for their relationship to coal properties at four sites where more than one coal was fired. There is no clear evidence from these data that coal played a part in combustible levels.

For example, at Sites I and J, the same two coals were tested. At Site I, the Kentucky coal (coal 2) gave the lowest combustible levels in the bottom ash while at Site J no difference was found. The same was true for combustibles in the flyash. Site J showed Kentucky coal producing higher combustible levels while Site I showed no change. It is concluded from these results that the apparent differences in combustibles at Sites I and J are not due to the coal. Perhaps they are the result of data scatter, or an unknown variable.

At Test Site D, Victoria coal appears to produce the highest bottom ash combustible levels. These data, shown in Figure 4-42, could also be misleading. Nothing could be found in the coal properties to account for this apparent difference. The difference is based on only two data points.

4.5.3 Sulfur Oxides vs Coal Properties

Sulfur balances were not successful on the mass fired overfeed stokers. The problem could lie with the representativeness of the coal sample, or with

TABLE 4-25

ASH BALANCE
MASS FIRED OVERFEED STOKERS

	Coal	Inorganic Ash as % of Coal Ash		As-Found Ash as %* of Coal Ash	
		% Carryover	% Grate	% Carryover	% Grate
Site D	1	9	91	12	98
	2	17	83	24	100
	3	11	89	15	139
Site H	1	11	89	15	112
Site I	1	10	90	14	139
	2	18	82	32	116
Site J	1	10	90	12	121
	2	10	90	15	113
Site K	1	15	85	23	158
	2	15	85	23	126
	3	19	81	29	183
	AVERAGE	13	87	19	128
	STD. DEV.	4	4	7	26

* As-Found Ash includes combustible material while Inorganic Ash does not.

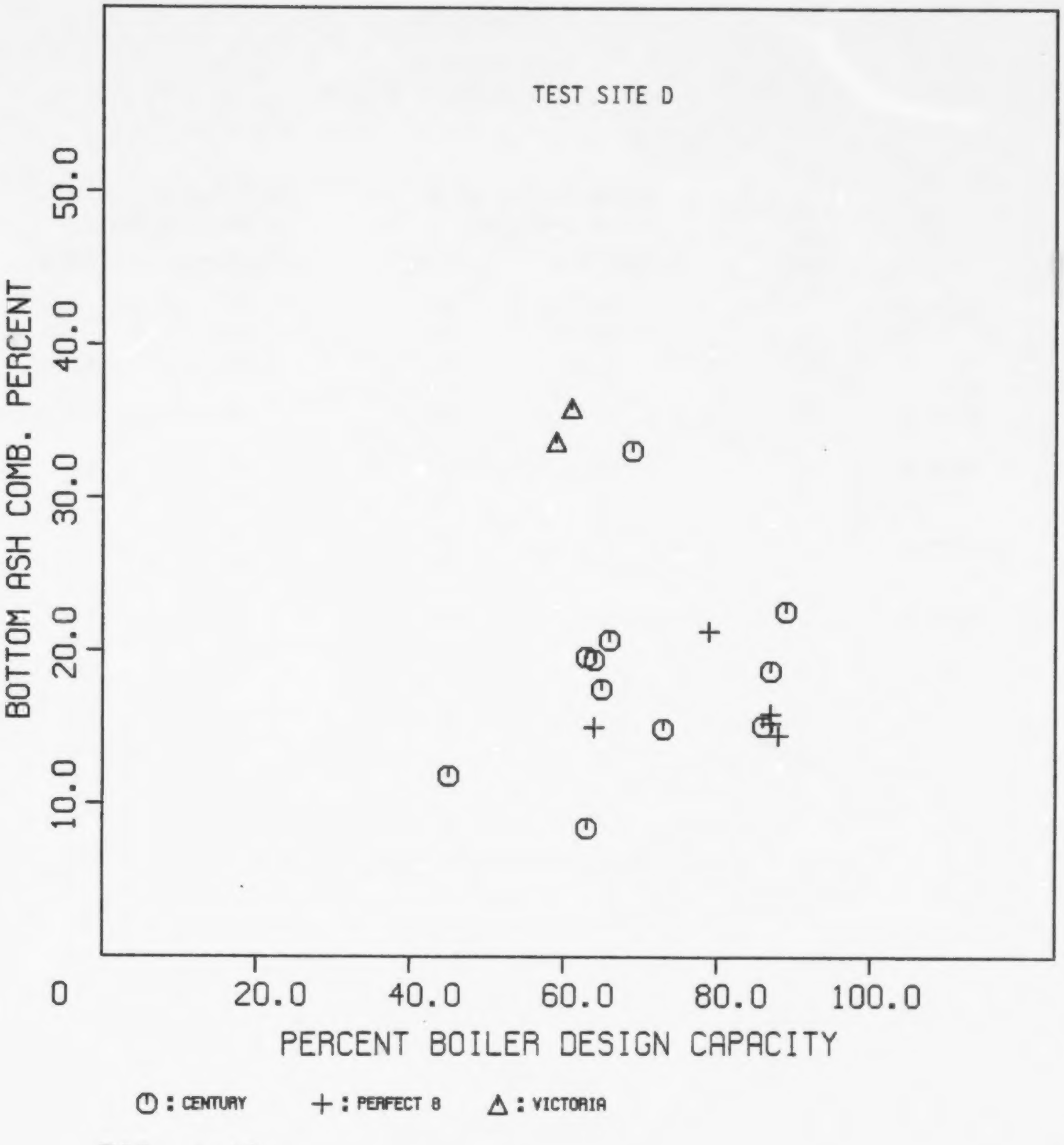

FIG. 4-42
BOTTOM ASH COMB. VS. PERCENT DESIGN CAPACITY

the analysis of the coal sample or flue gas sample. For whatever reason, the sulfur oxide data shown in Figure 4-43 do not correspond with the fuel sulfur as closely as they should.

An alternate measure of fuel sulfur conversion is obtained by measuring the sulfur retained in the ash and assuming the difference was converted to sulfur oxides. This method yields conversion efficiencies of 97 to 99%. The sulfur retention data are shown in Table 4-26.

TABLE 4-26

SULFUR RETAINED IN THE ASH

	Coal	% Retained in Flyash	% Retained in Bottom Ash	Total
Site D	1	.7	1.3	2.0
	3	.6	1.4	2.0
Site H	1	.4	2.9	3.3
Site J	1	.1	1.2	1.3
	2	.3	2.6	2.9
Site K	1	.2	.9	1.1
	AVERAGE	.4	1.7	2.1
	STD. DEV.	.2	.8	.9

The amount of sulfur retained in the bottom ash was found to be related to the sulfur content of the coal. The data substantiating this relationship is shown in Figure 4-44.

Sulfur trioxide was found to make up 1.4% or less of the total sulfur oxides in the flue gas. Sulfur trioxide was also found to increase as total sulfur oxides increased. These data are shown in Figure 4-45.

4.5.4 Nitric Oxide vs Coal Properties

Nitric oxide (NO) was found to be unrelated to fuel nitrogen. To make this correlation, the mathematical models previously developed in Section 4.4.3 were employed. Nitric oxide concentration was calculated with the model for

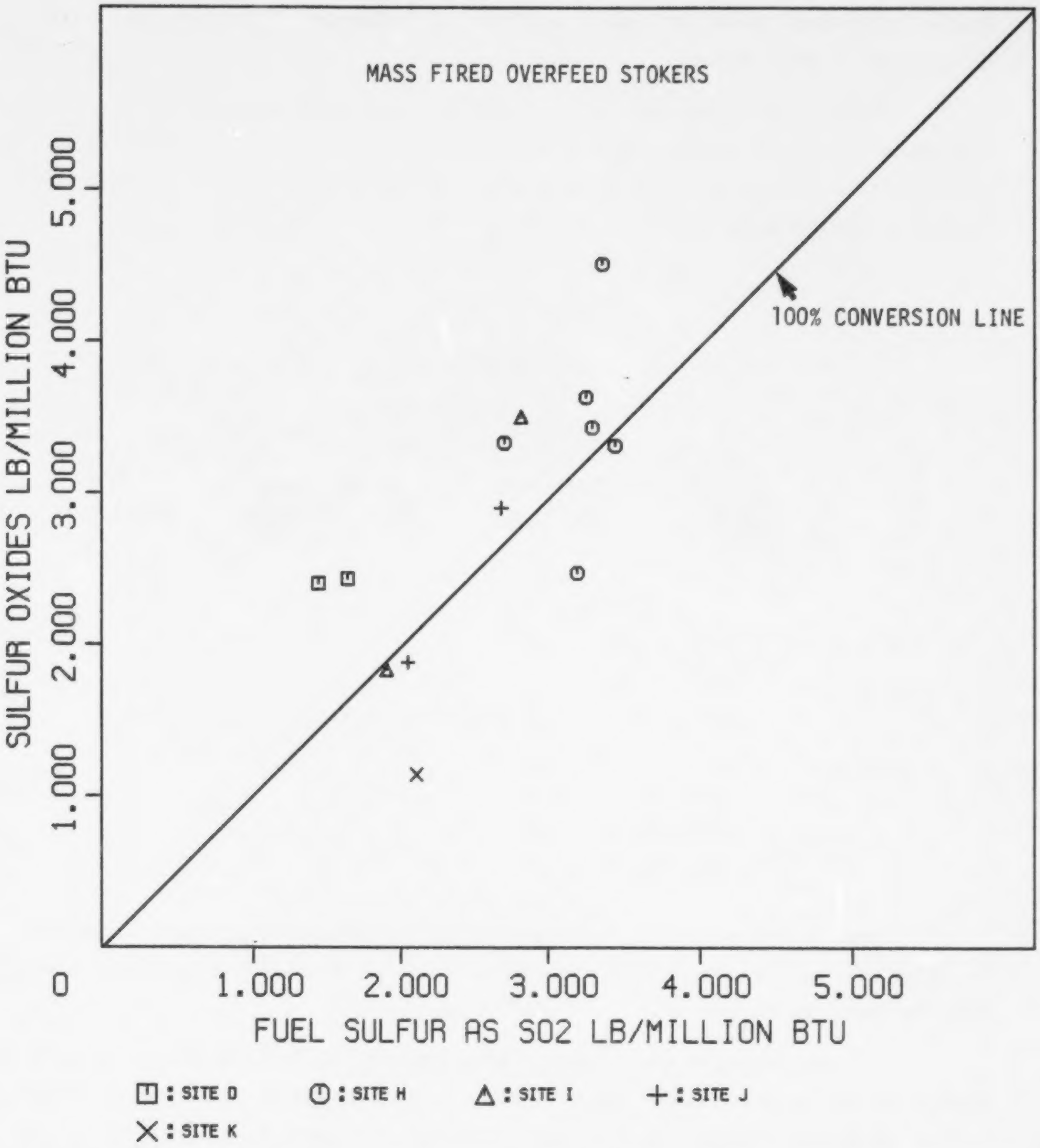

FIG. 4-43

SULFUR OXIDES VS. FUEL SULFUR AS SO2

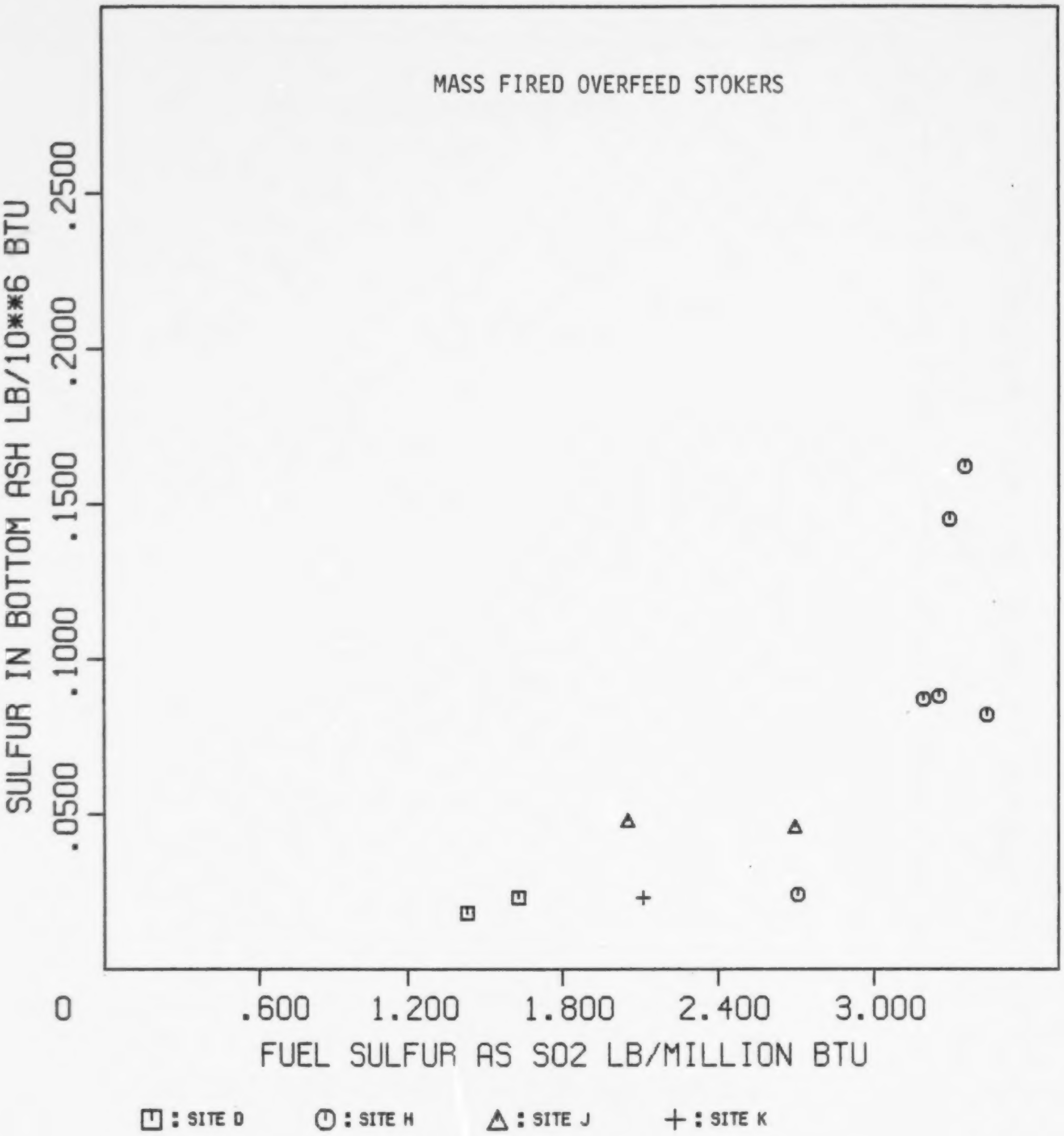

FIG. 4-44
SULFUR IN BOTTOM ASH VS. FUEL SULFUR AS SO2

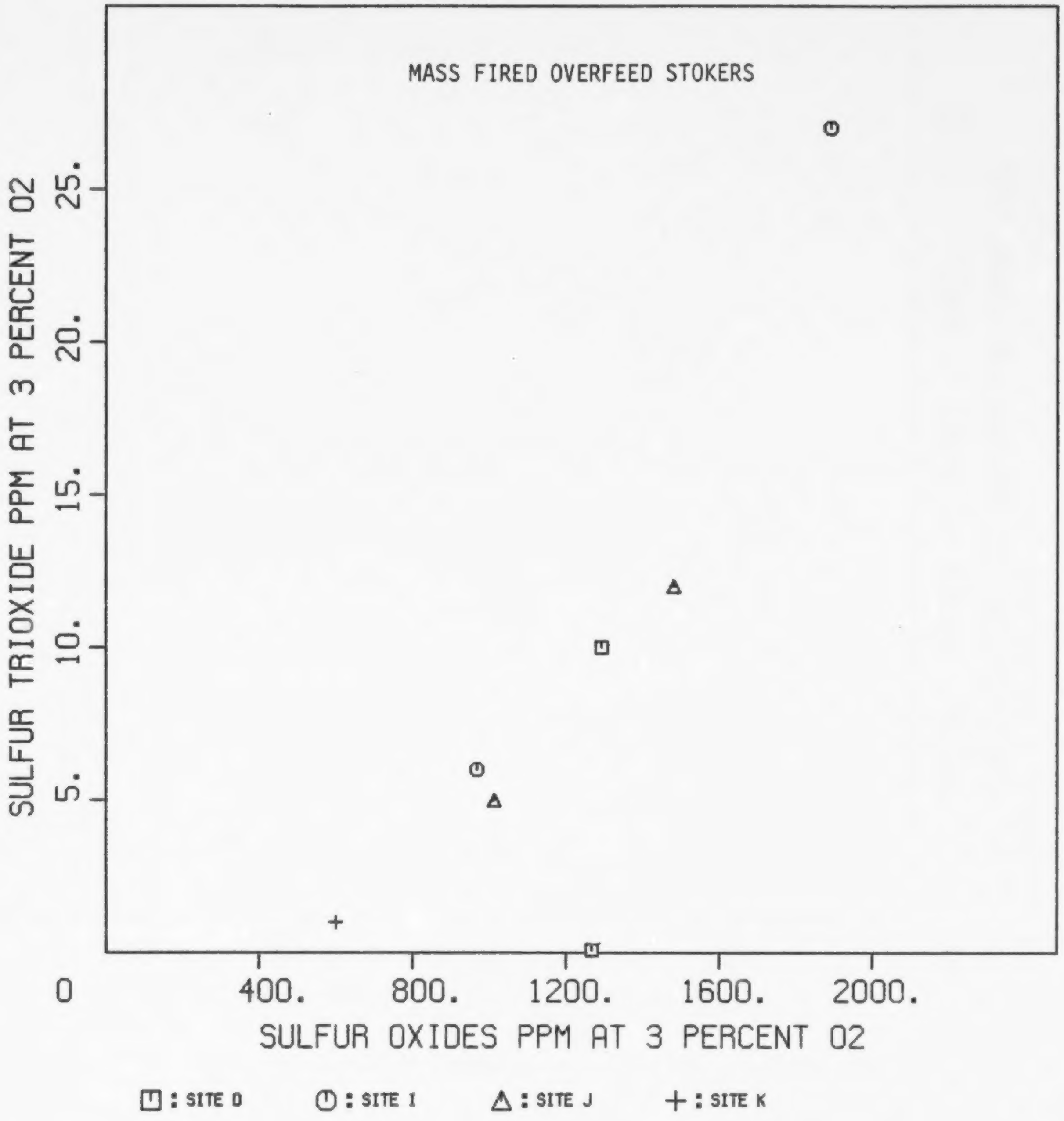

FIG. 4-45
SULFUR TRIOXIDE VS. SULFUR OXIDES

each test which included an ultimate coal analysis. The fuel nitrogen from the ultimate analysis was then plotted against the difference between the calculated nitric oxide and the measured nitric oxide.

Figure 4-46 illustrates the results for Test Site D. Although the highest fuel nitrogen test point correlated with the greatest positive deviation from the model, there is no indication of a trend.

Nitrogen dioxide (NO_2) was found in only very small concentrations. It was generally measured as zero but occasionally reached measurable concentrations of up to 13 parts per million. The highest measured concentration was less than 5% of the total nitric oxides in the flue gas.

4.5.5 Carbon Monoxide vs Coal Properties

Carbon monoxide was measured only at Sites D, H and K because the carbon monoxide monitor was out of service during testing at Sites I and J. No correlations were found between carbon monoxide levels and coal properties during these tests.

4.5.6 Unburned Hydrocarbons vs Coal Properties

Unburned hydrocarbons were measured at Sites H and J. There are insufficient data to correlate this emission with coal properties. At Site H only one coal was test fired, and at Site J only two hydrocarbon data points were obtained.

4.5.7 Boiler Efficiency vs Coal Properties

Test Site K was the only site at which coal properties varied significantly. At this site a washed coal, unwashed coal, and a washed and crushed coal all from the same mine were fired in the boiler. The washed coal and the washed and crushed coal had similar boiler efficiencies under similar operating conditions. The unwashed coal produced a lower boiler efficiency than either of the others because of its greater combustible heat loss. This increased combustible heat loss resulted not from an increase in the percentage of combustible material in the ash, but rather from the increased ash throughput. The unwashed coal's ash was 10% as compared to 4% for the washed coal. The data are given in Table 4-27.

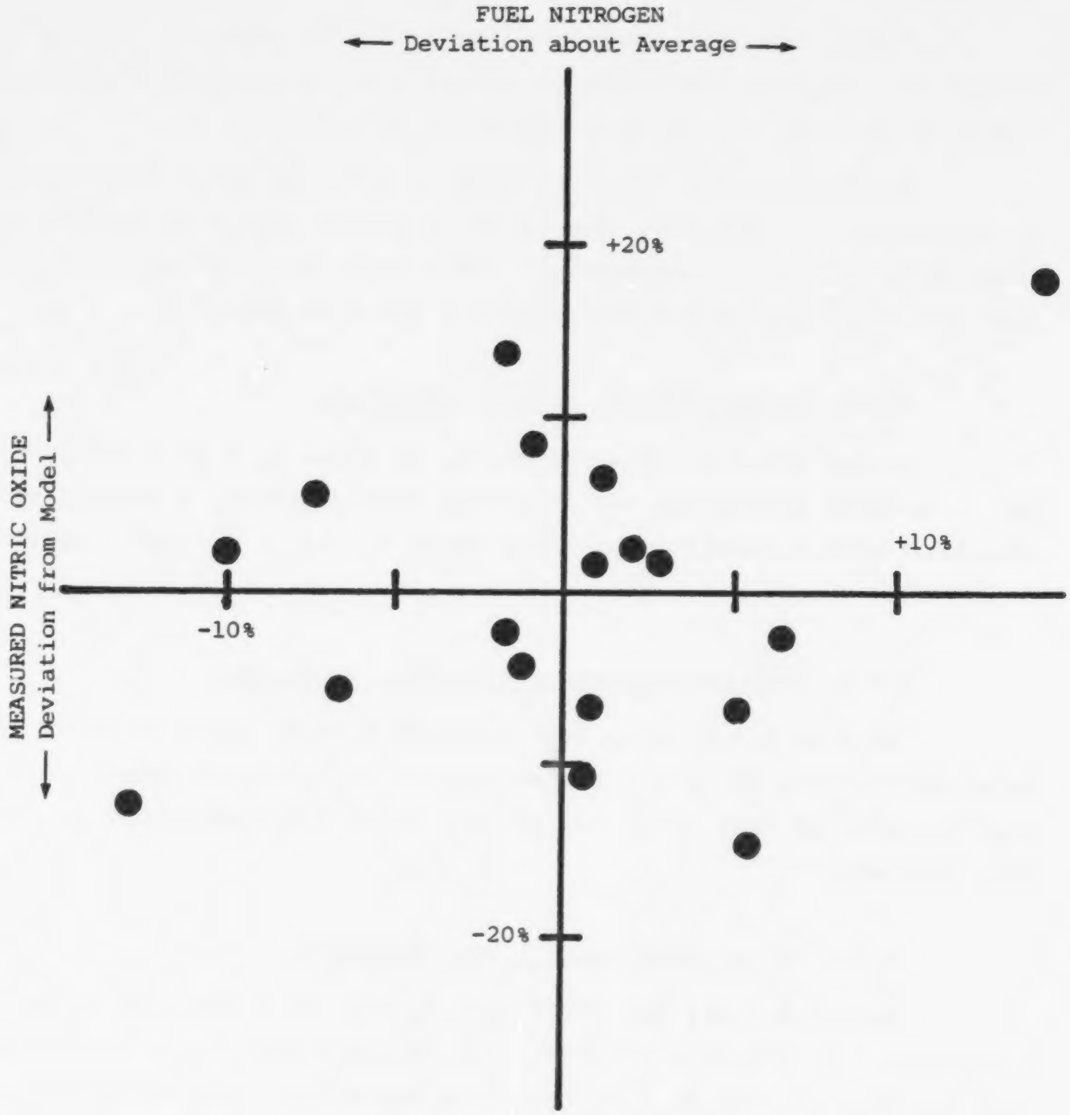

Figure 4-46. Nitric Oxide vs Fuel Nitrogen at Test Site D.

TABLE 4-27

BOILER EFFICIENCY VS COAL PROPERTIES
AT SITE K, HIGH LOAD

	Boiler Heat Losses				
Coal	Dry Gas	Moisture Related	Combustible	Other	% BOILER EFFICIENCY
Washed *	10.25	4.64	3.91	2.14	79.06
Unwashed	12.69	4.98	9.03	2.11	71.19
Washed & Crushed	12.00	4.87	3.15	2.35	77.63

* Washed coal data is average of four similar tests while the other two coals are represented by single tests.

4.6 RESPONSE TO OVERFIRE AIR

The purpose of overfire air in stoker-boilers is to control smoke and carbon monoxide emissions by providing turbulence for better mixing in the flame zone, and by holding the flame away from the cold water walls where it would be quenched. In these tests, overfire air was studied as an operating variable to determine its relationship to boiler efficiency and emissions. Boiler modifications were not included in the scope of this test program. Therefore, overfire air tests were limited to increasing and decreasing the overfire air flow rates through the existing jets. Tests were also run to determine overfire air flow rate as a function of static pressure in the overfire air headers. These tests indicate that at full load, overfire air supplies about 12% of the combustion air for the mass fired overfeed stokers studied.

Three of the boilers tested (Sites H, J and K) had only one row of overfire air jets. These overfire air jets were situated between 3.8 and 5.0 feet above the grate on the front wall, angled downward between 15° and 45°.

The remaining two boilers tested (Sites D and I) had two rows of overfire air jets on the front wall. The upper overfire air jets were 3.4 and 6.8 feet above the grate, respectively, and were angled downward by 30°. The lower overfire air jets were 1.4 and 4.5 feet above the grate, respectively, and angled downward by 10° and 45°, respectively.

4.6.1 Particulate Loading vs Overfire Air

Uncontrolled particulate emissions were observed to decrease for three of the five mass fired overfeed stokers tested when overfire air pressures were increased. Of the remaining two stokers, Site D showed conflicting trends, while Site J showed the opposite trend. Table 4-28 gives a summary of particulate emissions for varying overfire air settings.

Particulate emissions at Sites H, I and K were reduced by as much as 54% at the boiler outlet when overfire air pressure was increased from the minimum to the maximum settings. Part of this reduction can be attributed to more complete carbon burnout at Sites I and K. There was insufficient combustible data at Site H to correlate with overfire air. Figure 4-47 graphically illustrates the particulate reduction achieved at Site I by increasing the overfire air.

No definite trend occurred at Site D where mixed results were obtained. On Century coal, particulate emissions decreased with increasing overfire air pressure, and on Perfect 8 coal particulate emissions increased with increasing overfire air pressure.

Site J was the only site where particulate emissions increased with increasing overfire air under all test conditions. However, the percentage of fines in the coal was also higher during the high overfire air tests raising the possibility that fines were responsible for the increase in particulate emissions.

4.6.2 Combustibles in the Ash vs Overfire Air

The percentage of combustible material in the flyash decreased when overfire air pressure was increased. The percentage reduction in combustible material ranged from 12% to 40% in nine test sets, and averaged 27%. During one test set the combustible material increased by 13% when overfire air pressure was increased. The data are presented in Table 4-29. Figure 4-48 illustrates the data for Test Site I.

4.6.3 Nitric Oxide vs Overfire Air

Nitric oxide emissions were not influenced by overfire air pressure. No significant trend was seen for the five sites tested. Table 4-30 gives a summary of the nitric oxide emissions for the overfire air tests. Figure 4-49 presents the results of overfire air tests at Site D.

Attempts to set up staged combustion by use of the overfire air jets on the mass fired overfeed stokers were unsuccessful. Staged combustion is used successfully as a nitric oxide control strategy on burner fired combustion devices. However, on present design coal fired stokers it is not practical to produce fuel rich flame conditions at the grate because of clinker formation increase in opacity and grate overheating as undergrate air is reduced.

4.6.4 Carbon Monoxide vs Overfire Air

The effect of overfire air pressure on carbon monoxide emission levels is shown in Table 4-31. At Sites D, H and K, carbon monoxide emissions were reduced by 44% to 97% when overfire air pressures were increased. This reduction is the result of the overfire air induced turbulence in the flame zone. No carbon monoxide data were obtained at Sites I and J because the carbon monoxide monitor was out of service at these two sites.

Figure 4-50 presents the carbon monoxide data from Site K as a function of load and overfire air. The four high overfire air data points are the lowest emission levels.

4.6.5 Unburned Hydrocarbon vs Overfire Air

Unburned hydrocarbon emissions were examined as a function of overfire air pressure at Test Site H. At a low overfire air pressure of 3" H_2O, the unburned hydrocarbons were measured at 112 ppm @ 3% O_2 (wet). When the overfire air pressure was increased to 11-12" H_2O, the unburned hydrocarbon concentration dropped to 5-35 ppm. This represents an average 82% reduction in concentration due to the increased overfire air. The data are presented in Figure 4-51.

4.6.6 Boiler Efficiency vs Overfire Air

Boiler efficiency decreased by an average 2.75% when overfire air pressure was increased. Part of the decrease was due to increased dry gas loss due to an increase in the excess air. Another part of the decreased efficiency was due to an increase in the bottom ash combustible heat loss which may or may not be due to the increased overfire air.

The data, shown in Table 4-32, show the changes in the various heat loss categories for each test set in which overfire air was increased. The changes were not always consistent, but they resulted in decreased boiler efficiency in all but one case. The change in flyash combustible heat loss which was instrumental in the spreader stoker efficiencies, was too small to be instrumental in the efficiencies of these mass fired overfired stokers.

TABLE 4-28

EFFECT OF OVERFIRE AIR ON UNCONTROLLED PARTICULATE LOADING MASS FIRED OVERFEED STOKERS

				UNCONTROLLED PARTICULATE EMISSIONS lb/10^{6}Btu		
Site	Coal	% Design Capacity	Mean* Excess Air, %	Low OFA	High OFA	Percent Change
D	1	85	60	1.418	1.033 1.010	- 28
	2	88	55	0.837	1.097	+ 31
	2	64	77	0.694	0.793	+ 14
H	1	99	77	2.195	1.130 0.897	- 54
I	1	101	63	1.763	0.999	- 44
	1	100	41		0.904	
	2	101	55	1.430		
J	2, 1	100	61	0.699	0.984 1.442	+ 74
	2, 1	74	83	0.574	0.779	+ 36
	1, 2	49	107	0.369	0.617	+ 67
K	1	97	62	1.240 0.758	0.655	- 34
	1	99	49	0.755	0.639 0.850	- 2
	1	46	162	0.737	0.477	- 35

* Excess air increased with increasing overfire air pressures at sites D, H, I and J, but remained stable at Site K. Numbers shown are averages

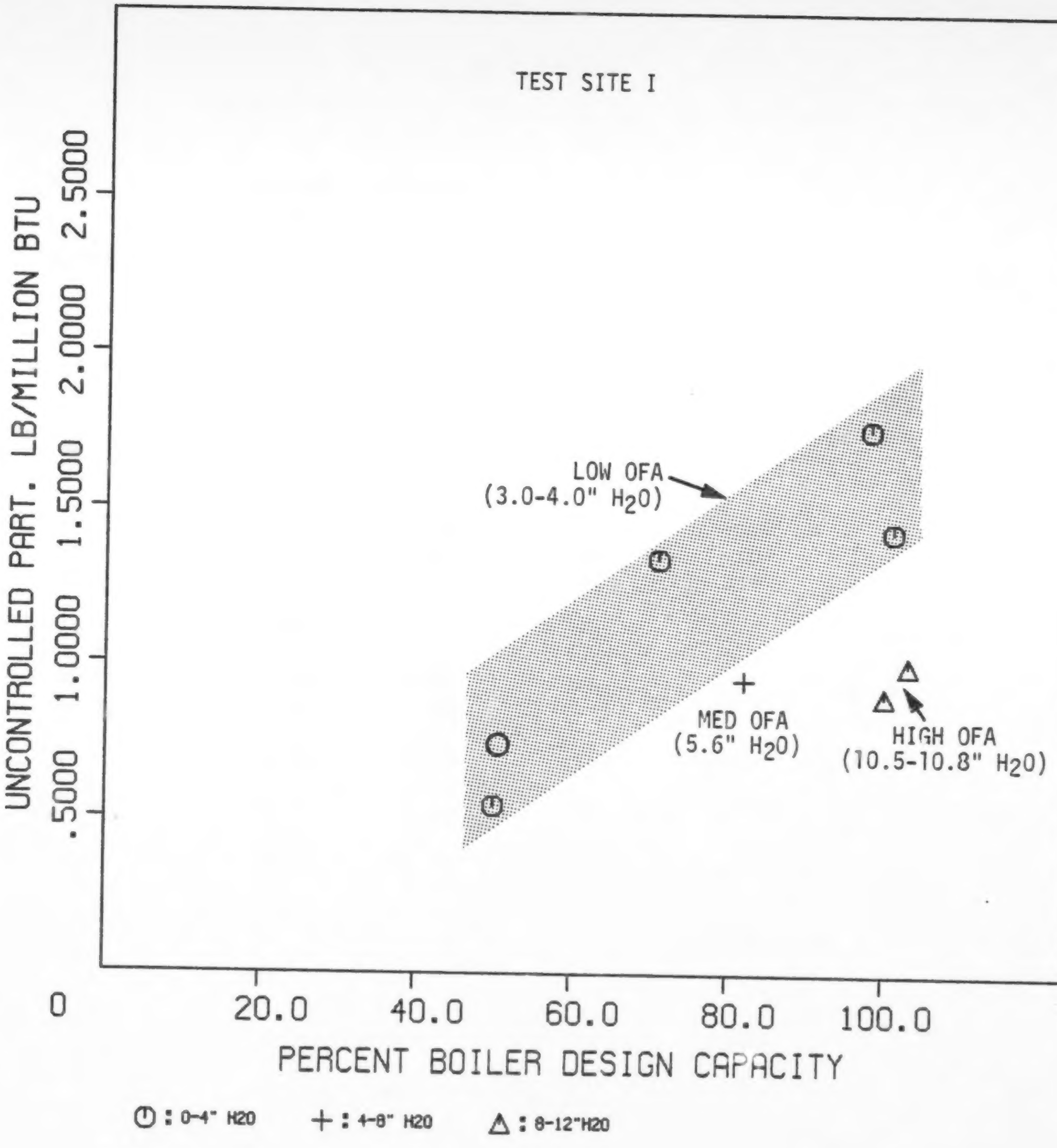

FIG. 4-47
UNCONTROLLED PART. VS. PERCENT DESIGN CAPACITY

TABLE 4-29

EFFECT OF OVERFIRE AIR ON COMBUSTIBLES IN FLYASH MASS FIRED OVERFEED STOKERS

				COMBUSTIBLE MATERIAL % by Weight		
Site	Coal	% Design Capacity	Mean Excess Air, %	Low OFA	High OFA	Percent Change
D	1	85	60	40.1	28.1 23.6	- 36
	2	88	55	28.2	22.1	- 22
	2	64	77	21.9	16.0	- 27
H	1	99	77	ND*	23.0 25.2	ND
I	1	101	63	36.7	22.0	- 40
	1	100	41	ND	25.6	ND
	2	101	55	ND	ND	ND
J	2, 1	100	61	26.8	ND 23.7	- 12
	2, 1	74	83	36.0	24.9	- 31
	1, 2	49	107	26.7	30.1	+ 13
K	1	97	62	32.2 36.7	29.4	- 15
	1	99	49	40.8	27.0 29.4	- 31
	1	46	162	36.0	24.0	- 33

* ND = No Data

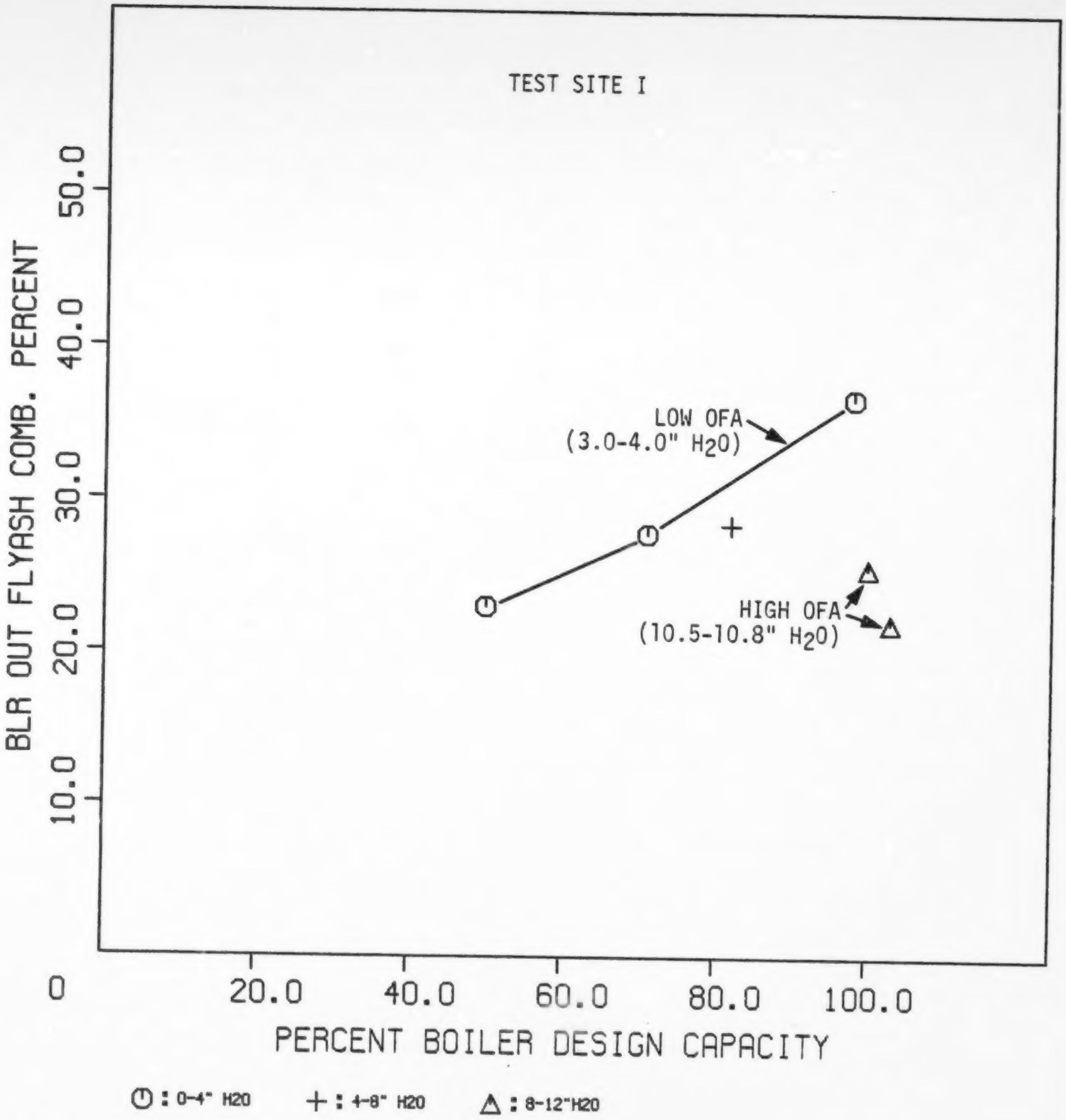

FIG. 4-48
BLR OUT FLYASH COMB. VS. PERCENT DESIGN CAPACITY

TABLE 4-30

EFFECT OF OVERFIRE AIR ON NITRIC OXIDE EMISSIONS
MASS FIRED OVERFEED STOKERS

Site	Coal	% Design Capacity	Mean Excess Air, %	NITRIC OXIDE* $lb/10^6 Btu$ Low OFA	High OFA	Percent Change
D	1	85	60	.368	.324 .343	- 9
	2	88	55	.334	.228	- 32
	2	64	77	.262	.297	+ 13
H	1	99	77	.371	.382 .305	- 7
I	1	101	63	--	.396	
	1	100	41	.279	.326	+ 17
	2	101	55	.242	.258	+ 7
J	2, 1	103	56	.282	.393	+ 39
K	1	97	62	.303 .300	.311	+ 3
	1	99	49	.302	.320 .353	+ 11
	1	46	162	.311	.303	- 3

* Calculated as NO_2

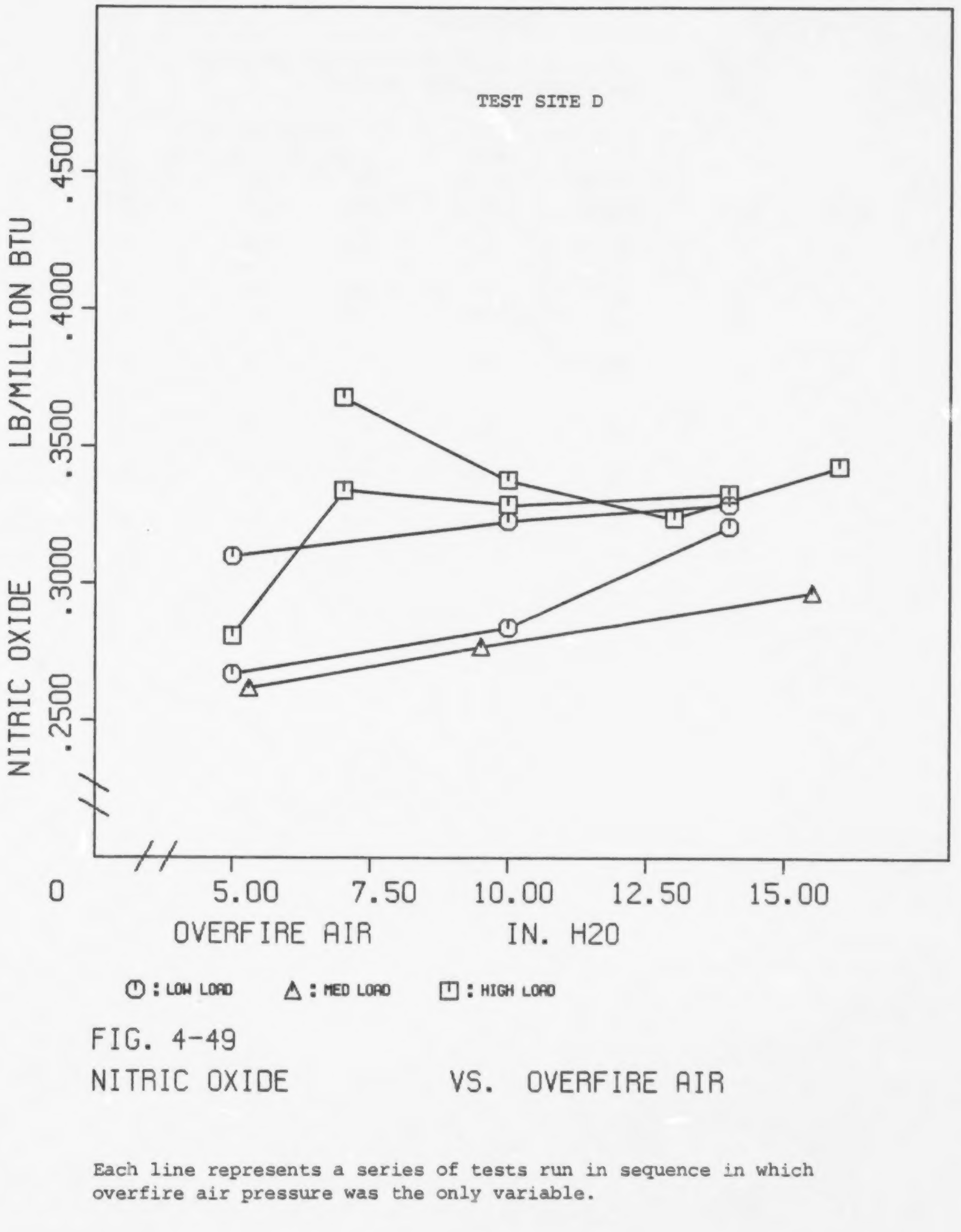

FIG. 4-49
NITRIC OXIDE VS. OVERFIRE AIR

Each line represents a series of tests run in sequence in which overfire air pressure was the only variable.

TABLE 4-31

EFFECT OF OVERFIRE AIR ON CARBON MONOXIDE EMISSIONS
MASS FIRED OVERFEED STOKERS

Site	Coal	% Design Capacity	Mean Excess Air, %	CARBON MONOXIDE PPM (DRY) @ 3% O_2		
				Low OFA	High OFA	Percent Change
D	1	85	60	618	34 39	- 94
	2	88	55	1.225	321	- 97
	2	64	77	87	29	- 66
H	1	99	77	513	41 69	- 89
K	1	97	62	537 275	70	- 83
	1	99	49	208	126 105	- 44
	1	46	162	339	187	- 45

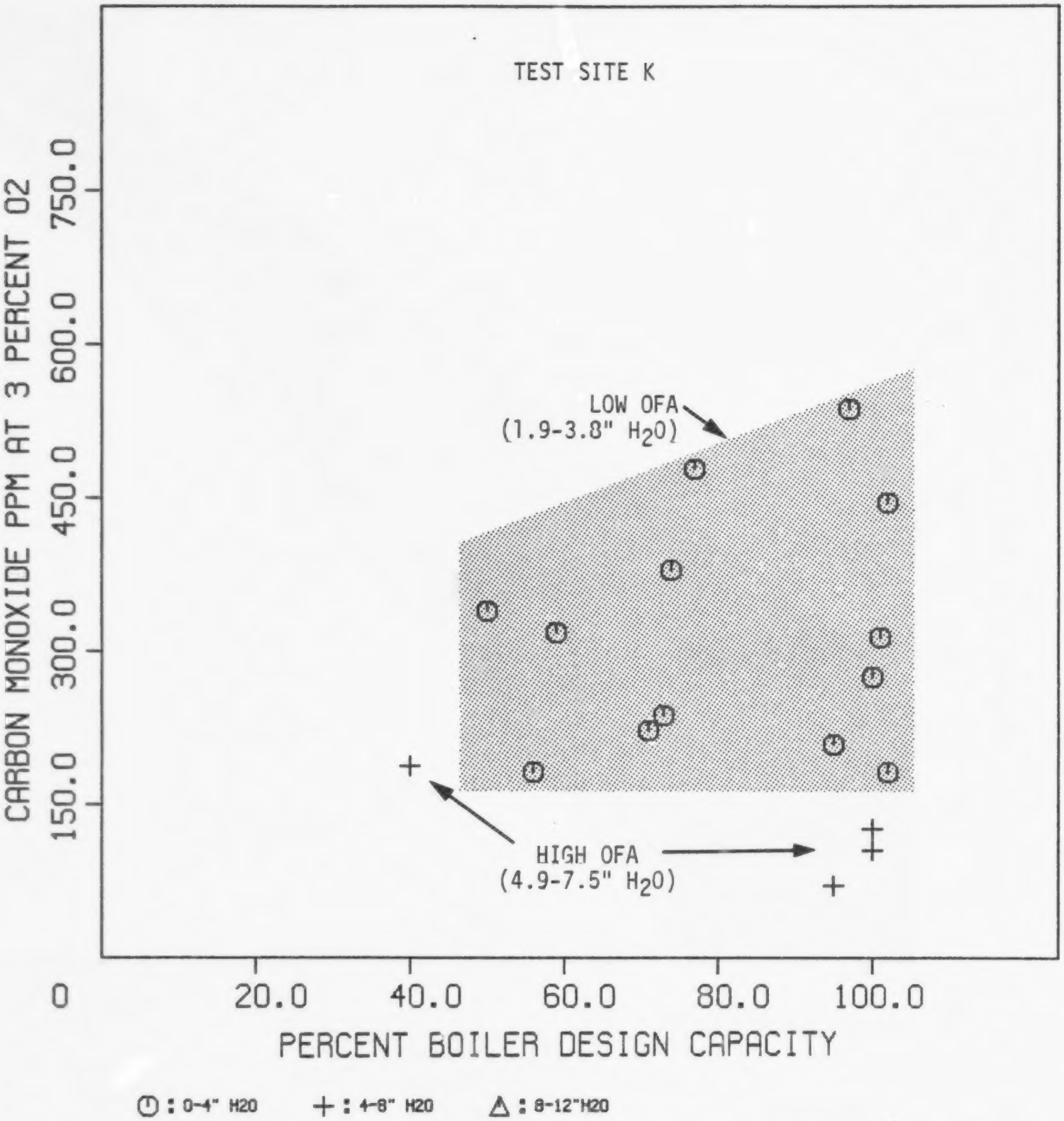

FIG. 4-50

CARBON MONOXIDE VS. PERCENT DESIGN CAPACITY

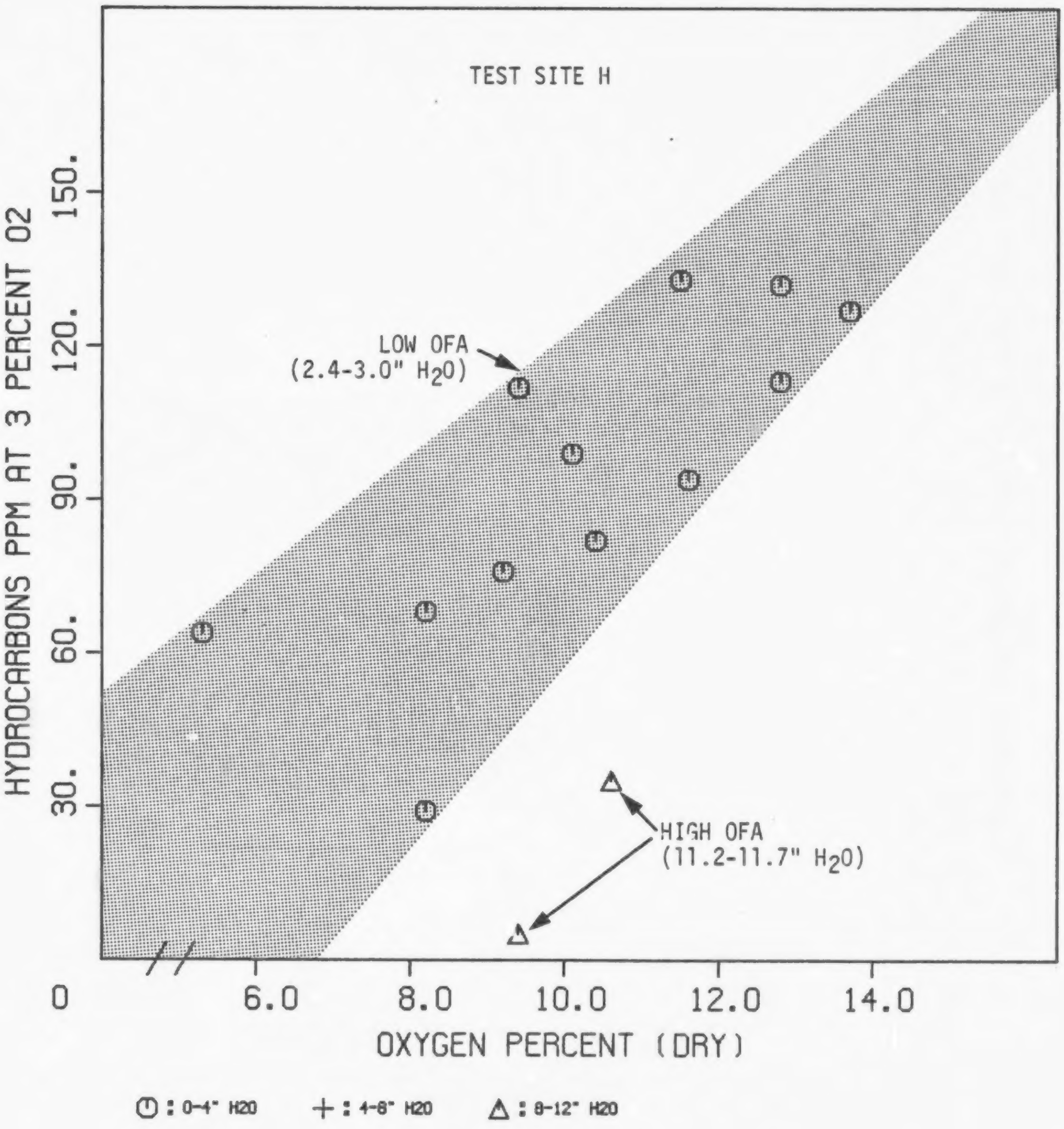

FIG. 4-51
HYDROCARBONS VS. OXYGEN

TABLE 4-32

EFFECT OF OVERFIRE AIR ON HEAT LOSSES AND EFFICIENCY
MASS FIRED OVERFEED STOKERS

		CHANGE IN PERCENT HEAT LOSS WHEN OVERFIRE AIR INCREASED						CHANGE IN BOILER EFFICIENCY
Site	Coal	Dry Gas	Fuel Moisture	H_2O From H_2	Flyash Combustibles	Bottom Ash Combustibles	Radiation	
D	1	.10	-.06	.01	-.37	-.01	.02	.31
	2	.85	.02	.01	-.18	-.63	.01	-.08
	2	.60	.02	.02	.00	.30	.02	-.96
H	1	1.08	.31	.23	ND	1.13	.03	ND
I	1	.83	-.05	.02	-.61	2.33	-.03	-2.49
	1	2.09	.10	.24	-.06	.77	-.01	-3.13
	2	2.65	-.05	.06	.04	.11	-.01	-2.80
J	2, 1	.18	.18	.24	.15	2.08	-.01	-2.82
	2, 1	3.79	.12	.31	-.01	-.95	.00	-3.26
	1, 2	.22	.02	.28	.12	-.58	-.03	- .01
K	1	.62	.06	.15	-.21	3.25	.01	-3.88
	1	.57	.16	.12	-.16	-4.47	-.03	-3.81
	1	-4.30	-.09	-.10	-.23	14.56	.28	-10.12
AVERAGE		.71	.06	.12	-.13	1.38	.02	-2.75
STD. DEV.		1.86	.11	.13	.22	4.39	.08	2.77

4.7 PARTICLE SIZE DISTRIBUTION OF FLYASH

Particle size distribution of the flyash was determined on the overfeed stokers by a variety of means. These include the Brink cascade impactor for Sites D, H, J, and K, the Anderson cascade impactor for Sites L2 and L4, the Bahco classifier for Sites D, H L2, and L4, SASS cyclones for Sites D, H, I, J, and K, and sieve analysis for Sites D and H. The drawbacks of each method were covered in detail in Section 3.8, Particle Size Distribution of Flyash, and will not be discussed again in this section.

The intent of these particle size distribution tests was to document the size distribution of the flyash under high load and normal operating conditions. No attempt was made to look at other variables such as overfire air, excess air, or coal properties.

4.7.1 Particle Size Distribution of the Uncontrolled Flyash

The particle size distribution test results are presented on log normal plots in Figures 4-52, 4-53, 4-54, and 4-55. Each plot represents a different particle sizing method and a different size distribution range. Figure 4-56 combines the mathematical average of each method on a single plot to give an overall view of the uncontrolled flyash size distribution for mass fired overfeed stokers and spreader stokers. It is clear that differences do exist between the various particle sizing methodologies. However, the data clearly show that mass fired overfeed stokers have a finer flyash than do spreader stokers.

The average and standard deviation of the data are presented in Table 4-33 for selected particle sizes. The sieve data, listed separately for lack of space in the table, averaged 29.6±14.4 below 44 micrometers, 50.5±16.5 below 100 micrometers, 85.7±12.0 below 300 micrometers, and 97.9±2.3 below 1,000 micrometers.

TABLE 4-33

AVERAGE SIZE DISTRIBUTION OF UNCONTROLLED FLYASH FOR OVERFEED STOKERS

	.3μm	1μm	3μm	10μm	20μm	44μm
Impactor Data	3.5±3.7	9.0±4.6	19.2±10.2	30.1±6.9	45.3±4.8	68.7± 1.3
Bahco Data	--	--	3.0± 1.9	14.5±6.5	27.0±8.4	62.6±17.8
SASS Data	--	--	9.4± 5.0	14.7±5.9	21.0±5.2	--

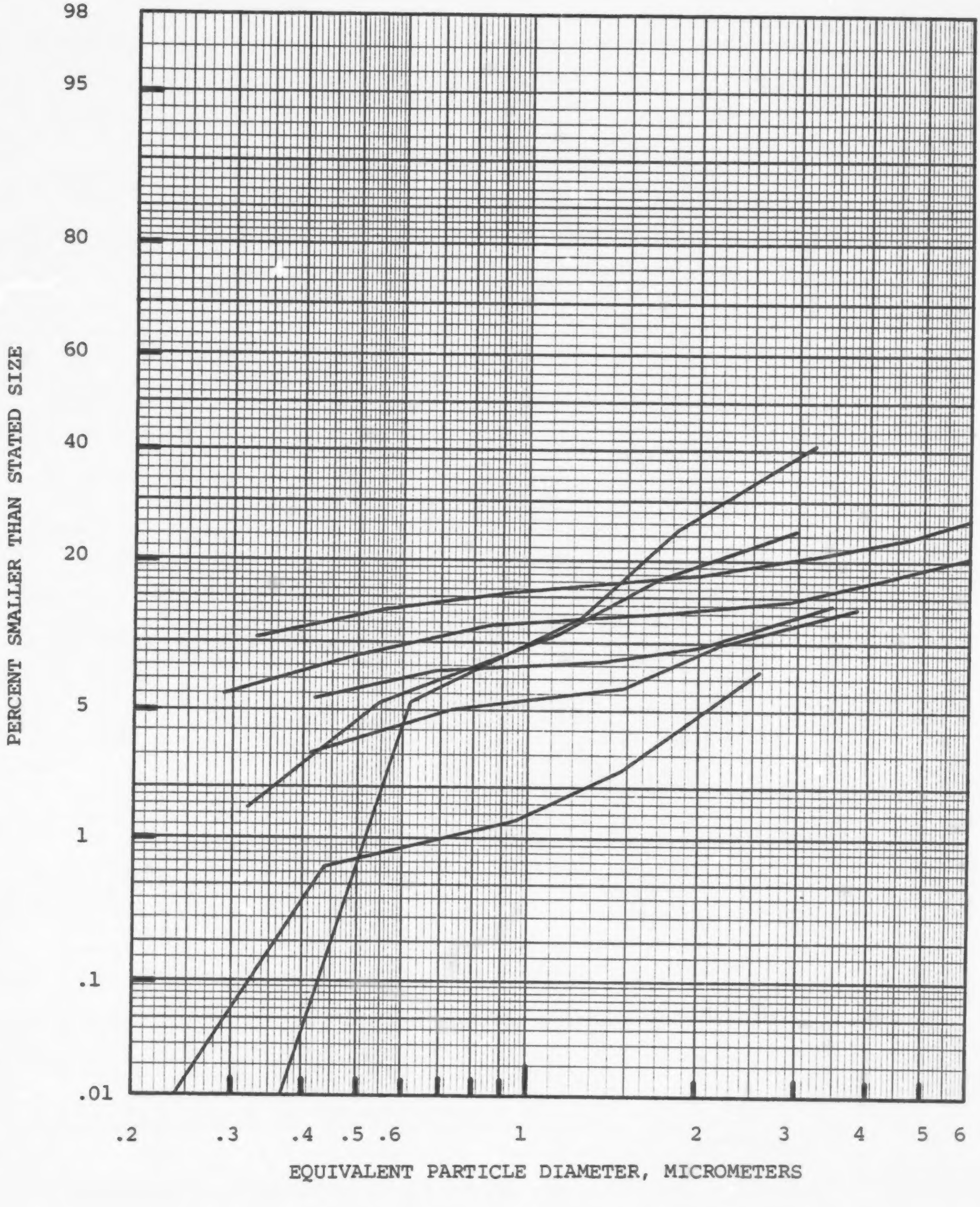

Figure 4-52. Particle Size Distribution at the Boiler Outlet as Determined by Cascade Impactor. Data are from Full Load Tests on Mass Fired Overfeed Stokers.

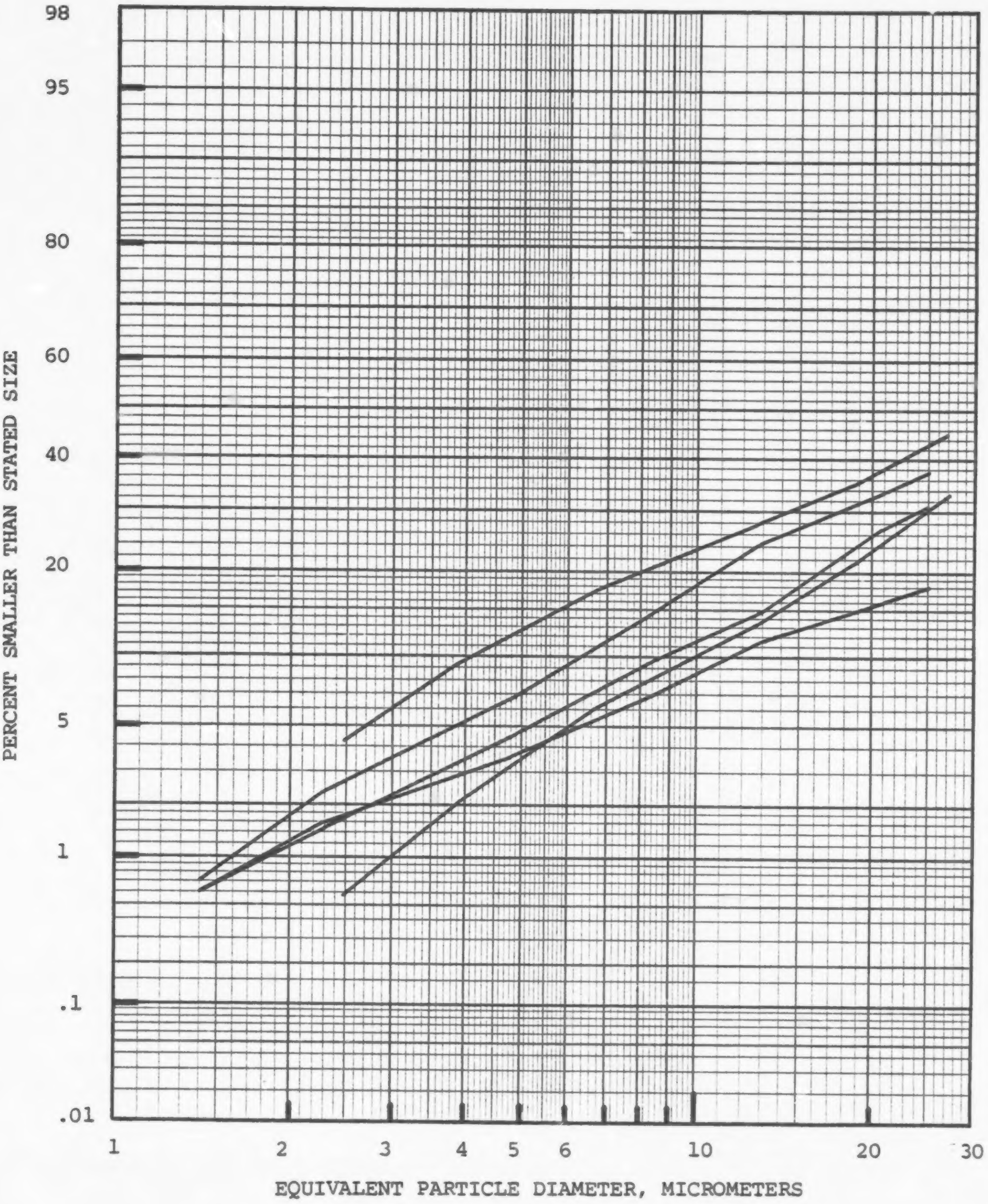

Figure 4-53. Particle Size Distribution at the Boiler Outlet as Determined by Bahco Classifier. Data are from Full Load Tests on Mass Fired Overfeed Stokers.

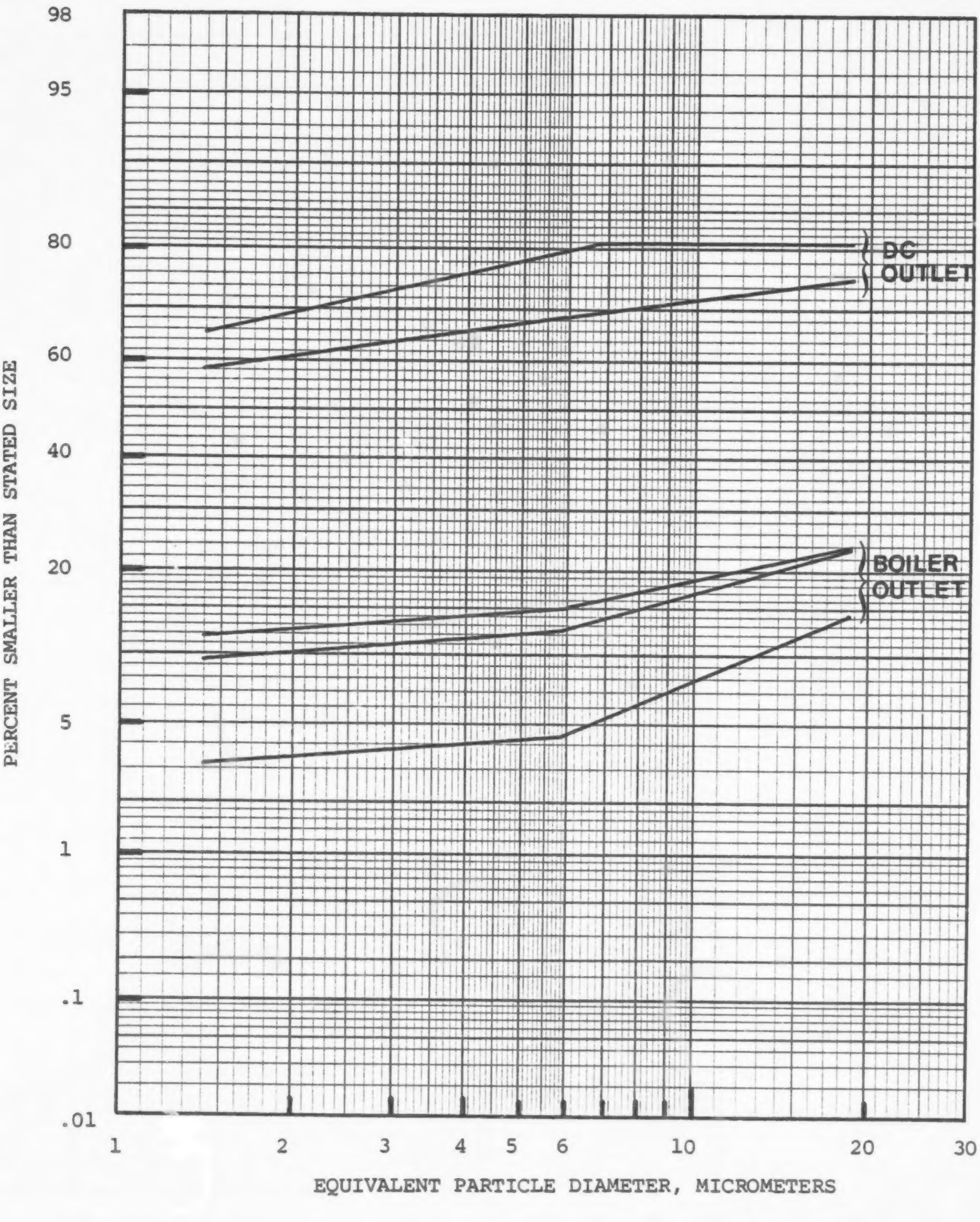

Figure 4-54. Particle Size Distribution at the Boiler Outlet and After the Mechanical Collector as Determined by SASS Cyclones. Data are from Full Load Tests on Mass Fired Overfeed Stokers.

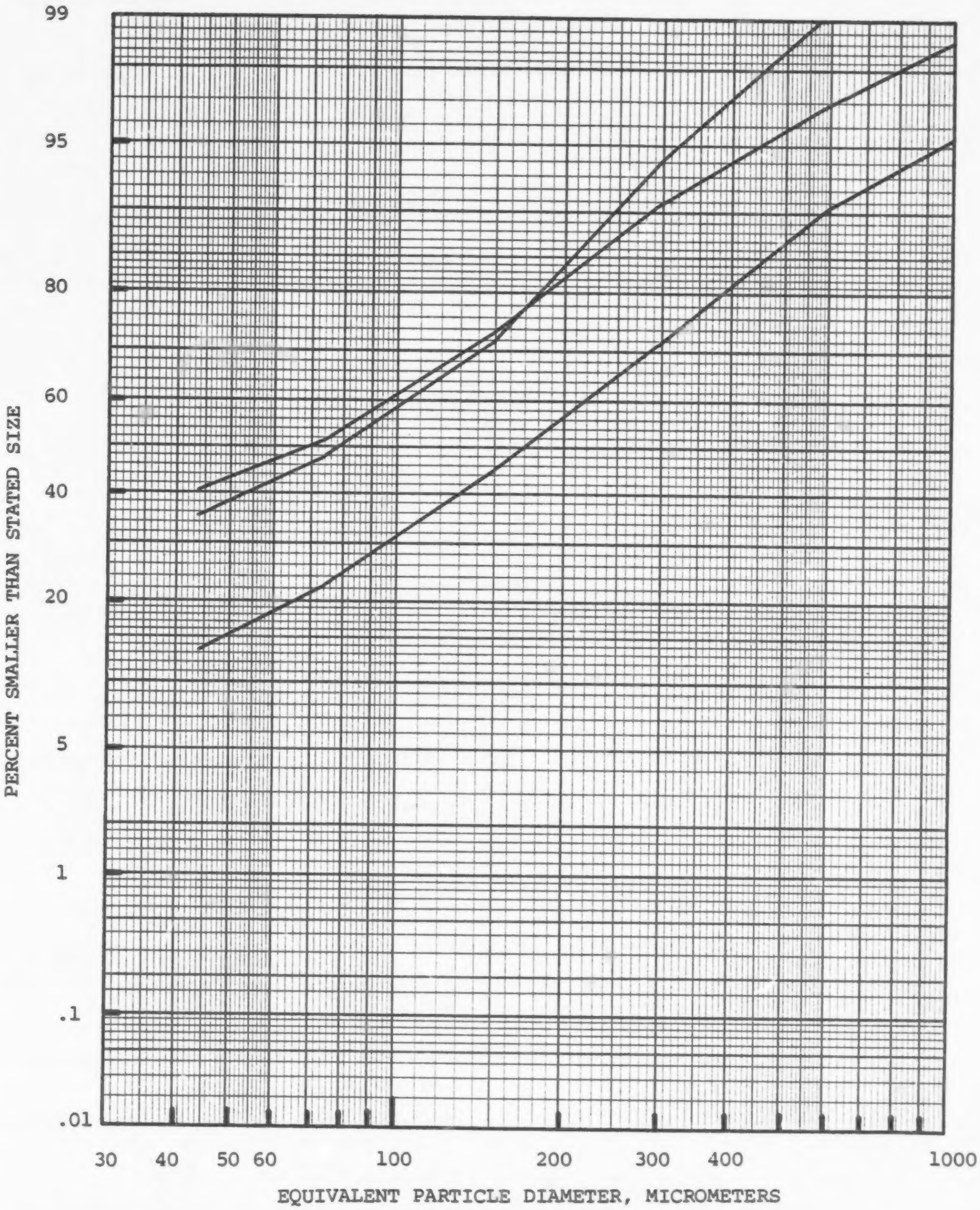

Figure 4-55. Sieve Analysis of Flyash Collected at the Boiler Outlets of Two Mass Fired Overfeed Stokers.

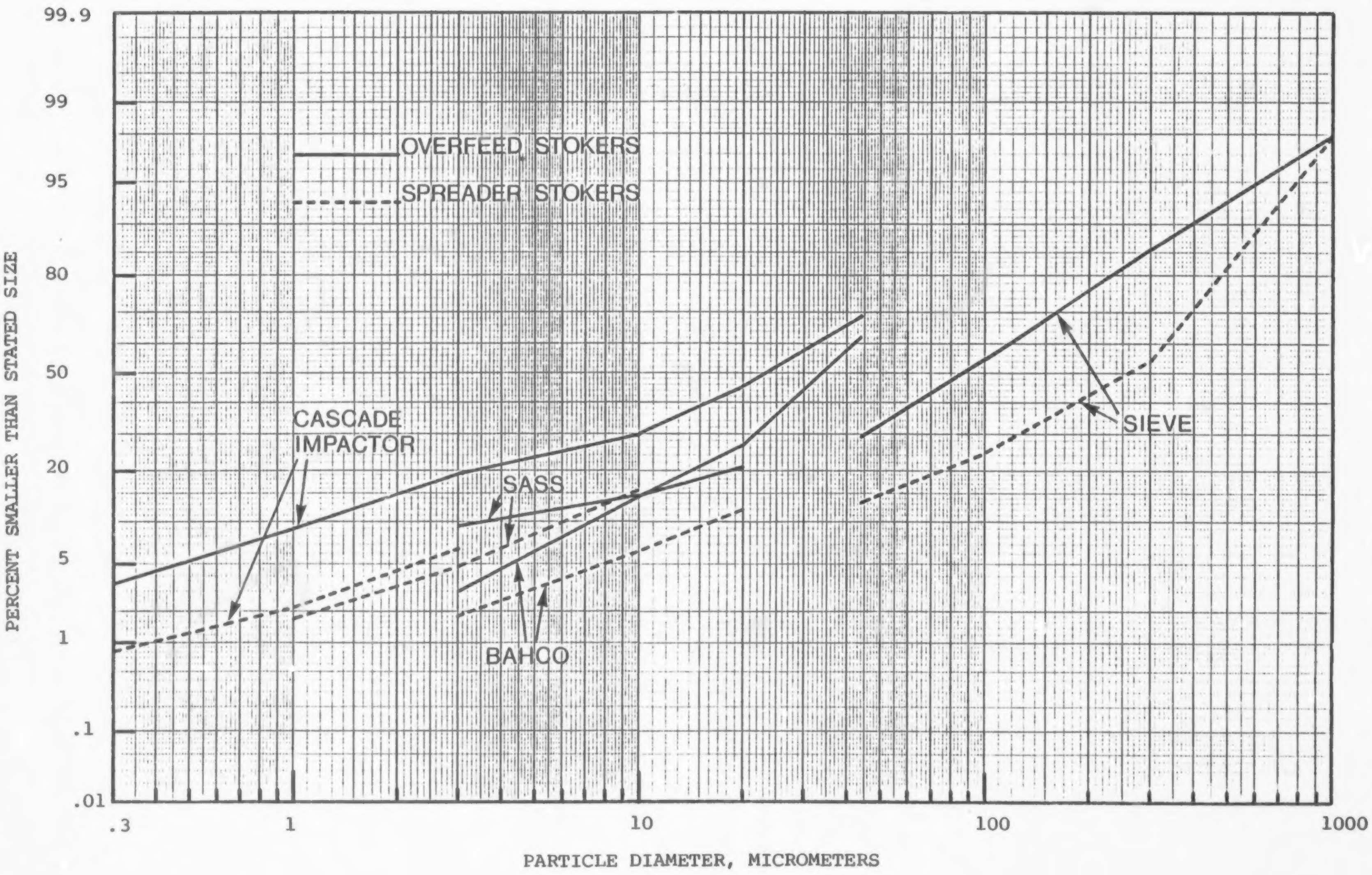

Figure 4-56. Average Particle Size Distribution at the Boiler Outlet as Determined by Four Different Methods. The Spreader Stoker Data are Included with the Mass Fired Overfeed Stoker Data for Comparison.

4.7.2 Particle Size Distribution of the Controlled Flyash

Size distribution data was obtained after the dust collector at Sites J, L2, and L4. This data, representing several different methodologies, is presented in Figure 4-57. Sites L2 and L4 appear to have a coarser particulate matter after the dust collector than Site J. This corresponds with their lower dust collector efficiencies.

4.7.3 Combustibles vs. Particle Size Distribution

The variation of combustible content with particle size was investigated at Test Sites D and J. At Test Site D, four boiler hopper ash samples were obtained and sieved into five size fractions. Each fraction was analyzed for combustible content. The results for all four samples were nearly identical. The average results are presented in Table 4-34. The larger sized particles clearly contained the highest combustible fractions.

TABLE 4-34

COMBUSTIBLES VS. BOILER HOPPER ASH - SITE D

Tyler Screen Mesh	Average Diameter Micrometers	Mass %	Combustibles %
- 8 + 16	1,325	3	74
-16 + 35	713	17	29
-35 + 80	303	44	8
-80 + 200	128	24	8
- 200	38	12	8
		Weighted Average:	14%

Nine ash samples collected from the dust collector hopper at Test Site J were also analyzed. This time, however, the samples were only divided into two size ranges. The results, given in Table 4-35, again show that the larger particles contain the higher combustible fraction.

TABLE 4-35

COMBUSTIBLES VS. DC HOPPER ASH - SITE J

Tyler Screen Mesh	Average Diameter Micrometers	Mass %	Combustibles %
- 20 + 100	490	18	43
- 100	74	82	21

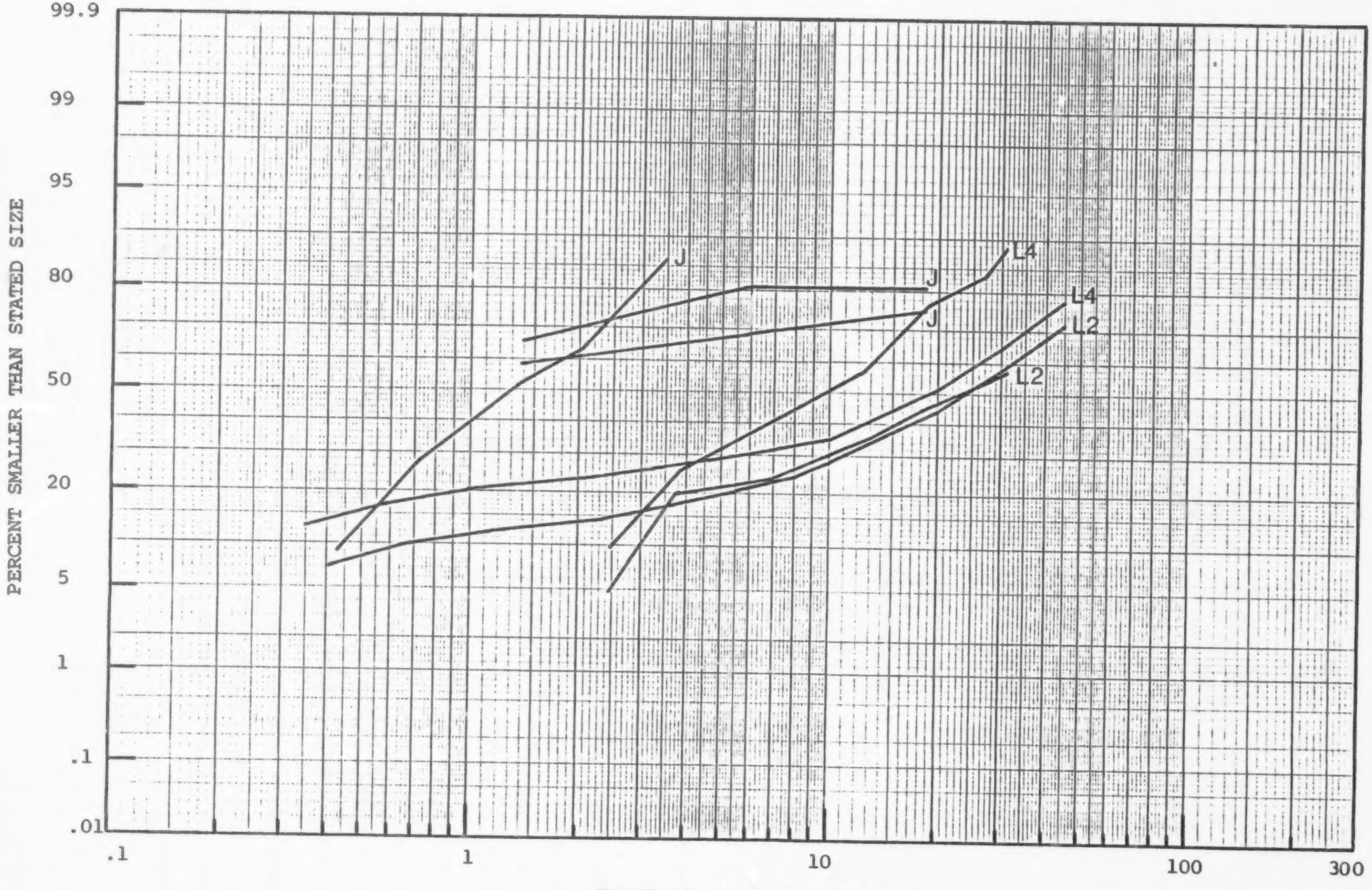

Figure 4-57. Particle Size Distribution After the Mechanical Collector of Three Mass Fired Overfeed Stokers. Data Represents Several Measurement Methodologies.

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4.7.4 Dust Collector Efficiency vs. Particle Size Distribution

Dust collector efficiency with respect to particle size was calculated from size distribution data obtained at the inlet and outlet of the dust collector at Sites L2 and L4. These results are summarized in Table 4-36.

TABLE 4-36

EFFICIENCY WITH RESPECT TO PARTICLE SIZE

Particle Size Ranges Micrometers	Collector Efficiency		
	Site L2 Impaction Results	Site L2 Bahco Results	Site L4 Impaction Results
125 - 30	13.2	21.2	3.2
30 - 20	5.6	22.3	0.0
20 - 10	0.0	0.0	2.3
10 - 1	9.8	0.0	4.7
Overall Efficiency	8.9	7.2	2.8

The dust collector efficiencies of these two units are very low. The three other units with dust collectors, Sites D, J, and K, had higher collection efficiencies. When collector efficiency is plotted as a function of mass percent of particulate material smaller than 20 micrometers, a loose correlation is found. This is shown in Figure 4-58.

Figure 4-59 shows how dust collector efficiency behaved as a function of load on three mass fired overfeed stokers. In each case, there was a tendency for efficiency to drop off as load decreased.

There are many other variables which play a part in dust collector efficiency. These include the collector's design, state of repair, inlet dust loading, and pressure drop through the cyclone tubes. These variables are not included in this analysis.

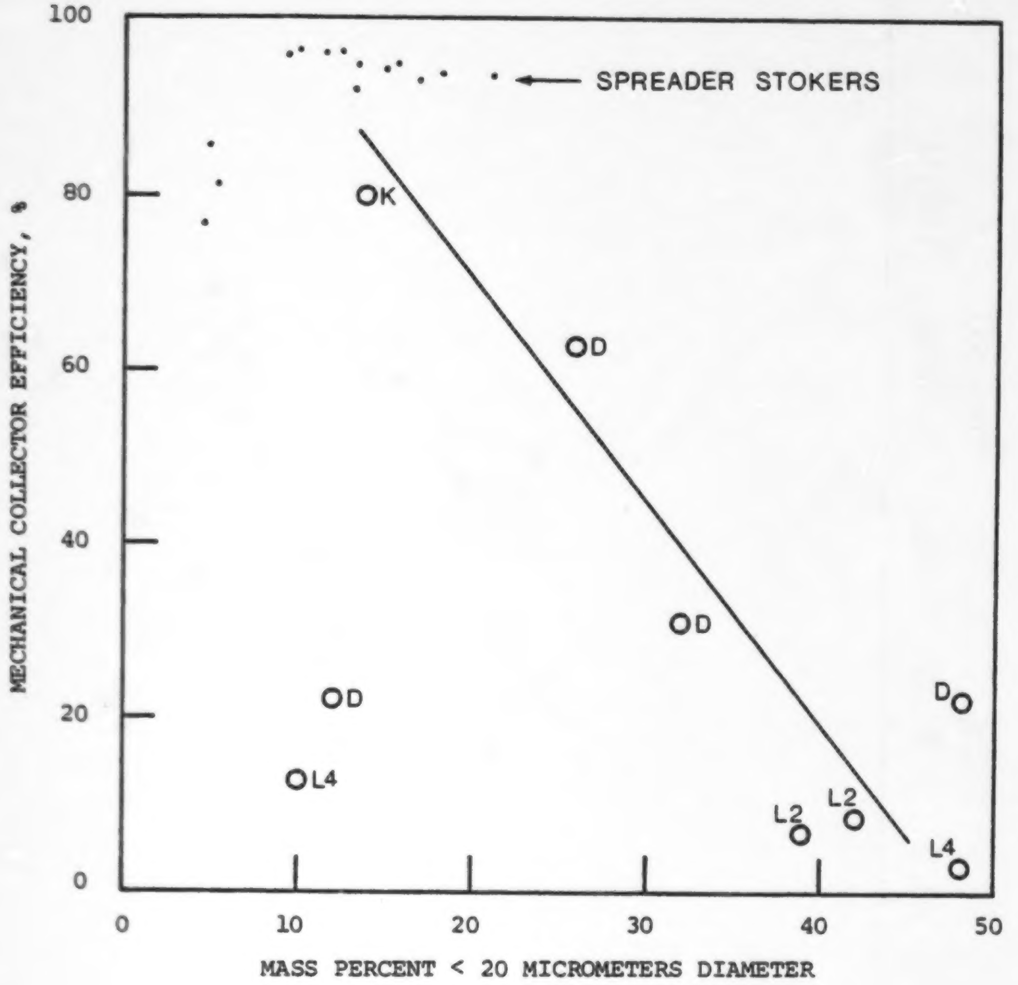


Figure 4-58. Relationship Between Percentage of Particles Smaller than 20 Micrometers and Dust Collector Efficiency for Mass Fired Overfeed Stokers. Data Represents Several Methods of Measurement and Boiler Loads Ranging from 60 to 100% of Capacity. Dots Represent Spreader Stoker Data for Comparison. Line Represents an Observed Trend.

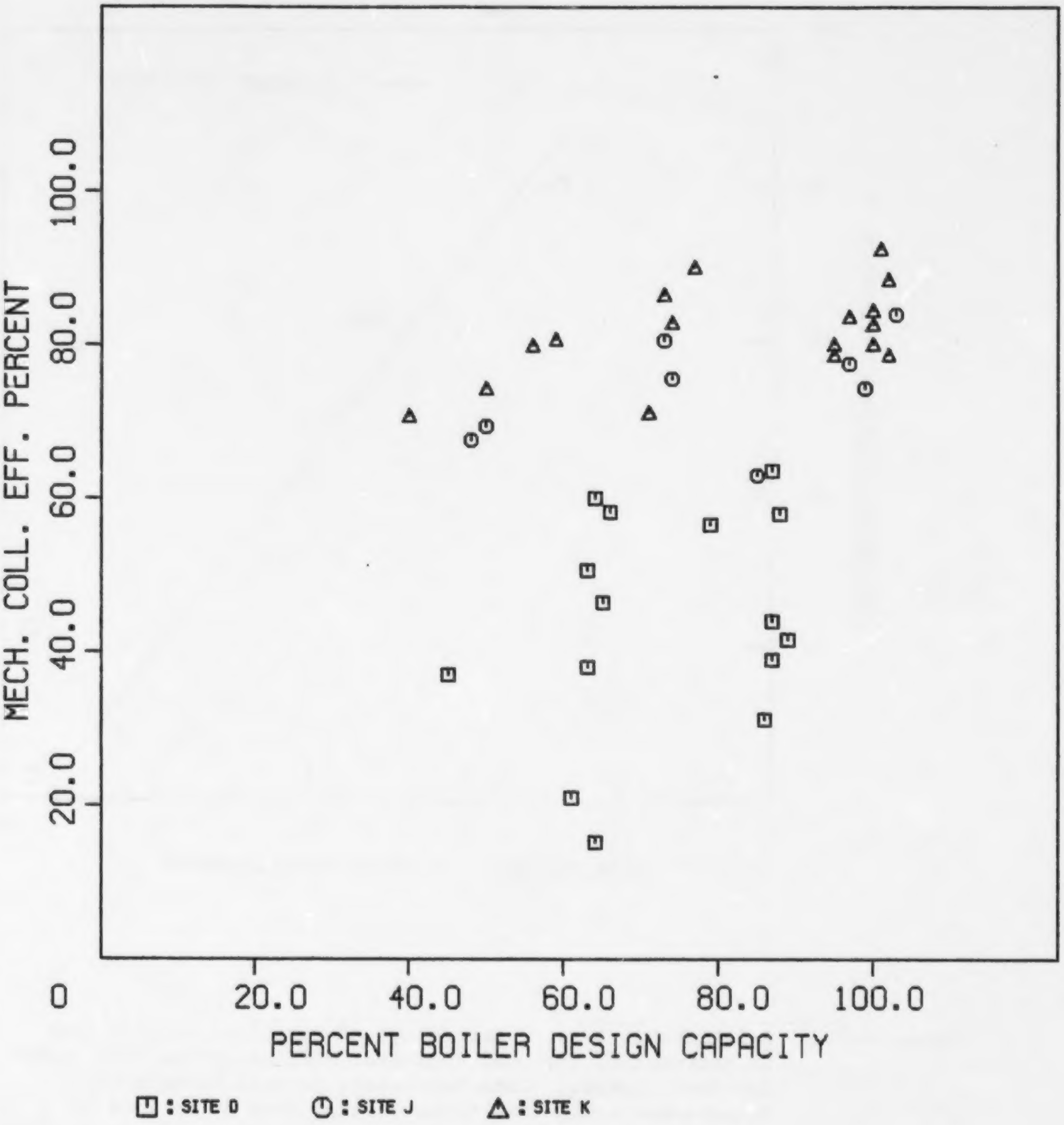


FIG. 4-59
MECH. COLL. EFF. VS. PERCENT DESIGN CAPACITY

5.0 MASS FIRED UNDERFEED STOKERS

This section of the report is organized differently than Sections 3.0 Spreader Stokers and 4.0 Mass Fired Overfeed Stokers because each of the five underfeed stokers discussed in this section was tested under a single operating condition, and for a more limited number of parameters.

5.1 DESCRIPTION OF UNITS TESTED

Mass fired underfeed stokers differ from mass fired overfeed stokers in that coal is introduced to the grate through retorts at a level below the location of air admission to the fuel bed, instead of from above. Ash can be discharged continuously at the rear of the stoker into the ash pit or it can be discharged by intermittent dumping from either the side or the rear of the stoker.

The five underfeed stokers studied in this program were tested under normal operating conditions with boiler loads ranging from 55 to 100 percent of design steaming capacity. The types of mass fired underfeed stokers tested include one single retort and four multiple retort stokers. The five units represent typical state-of-the-art designs firing bituminous coals, and were installed between 1950 and 1968.

Two of the units tested are equipped with cyclone dust collectors. However, the three units not equipped with dust collectors discharge into expansion breechings and tall stacks that provide a degree of emission control. Table 5-1 provides a brief description of the five units tested. Tables 5-2 through 5-6 and Figure 5-1 describe the combustion equipment in more detail.

5.2 COAL ANALYSIS AND SIZING

Coal delivery to each site was by truck. It was received into an outdoor truck hopper and transported to an overhead bunker which fed into a suspended weigh lorry. Coal sampling during each test was from the weigh lorry. Samples were tested by the Pennsylvania Bureau of Standards for proximate analysis,

TABLE 5-1

DESCRIPTION OF MASS FIRED UNDERFEED STOKERS TESTED

Site	Year Built	Rated Steaming Capacity lb/hr	*Peak Steaming Capacity lb/hr	Stoker Type	Dust Collector
L1	1966	26,000	34,500	Multiple Retort	Yes
L3	1956	23,300	31,000	Single Retort	No
L5	1950	28,460	38,000	Multiple Retort	No
L6	1957	20,000	27,000	Multiple Retort	No
L7	1968	50,000	55,000	Multiple Retort	Yes

*Peak Steaming Capacity was used throughout in the Site L Report

heating value, sulfur, ash softening temperature, and free swelling index. These data are presented in Tables 5-7, 5-8, and 5-9. Coal samples for three of the sites were also sized at the Mineral Preparation Laboratory of the Pennsylvania State University. These data are presented in Table 5-10.

The coals fired at all five sites were very similar with a few exceptions. As shown in Table 5-7, four of the five coals are classified as high volatile A bituminous coals. One of the coals is classified as a low volatile bituminous coal.

The proximate analysis given in Table 5-8 shows that the inherent moisture, ash, and heating value are nearly identical for all five coals. Fuel sulfur was highest at Site L1 where it was 3%, but was quite similar among the other four sites.

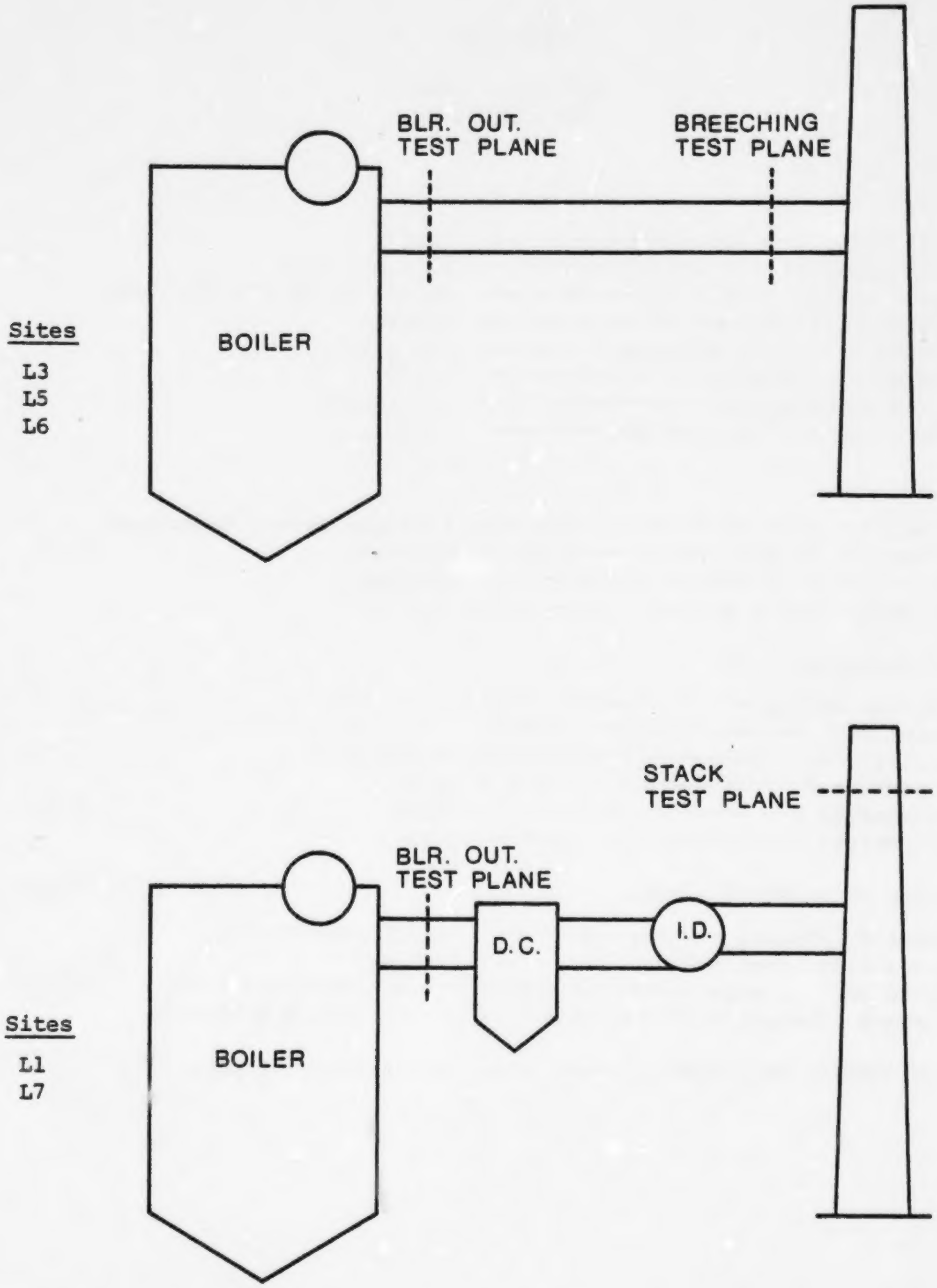

BLR. OUT. TEST PLANE
BREECHING TEST PLANE
Sites
L3
L5
L6
BOILER
STACK TEST PLANE
BLR. OUT. TEST PLANE
D. C.
I. D.
Sites
L1
L7
BOILER

Figure 5-1. Boiler Schematics for the Underfeed Stokers

TABLE 5-2

EQUIPMENT DATA
TEST SITE: L1

BOILER:	
Year Built	1966
Configuration	Multiple Pass
Rated Steaming Capacity	26,000 lb/hr (34,500 peak)
Design Pressure	Unknown
Actual Operating Pressure	125 psig
Feedwater Temperature	212°F
Steam Temperature	Saturated
Operating Air Temperature	Ambient
STOKER:	
Classification	Multiple Retort Underfeed
Effective Length	Unknown
Width	Unknown
Effective Grate Area	97.3 Ft^2
HEATING SURFACES:	
Furnace Volume	1,225 Ft^3
Water Wall	717 Ft^2
Boiler	4,283 Ft^2
Superheater	None
Economizer	None
Air Heater	None
HEAT RATES AT RATED CAPACITY:	
Input to Furnace	45,300,000 Btu/hr
Grate Width Heat Release	Unknown
Grate Heat Release	466,000 Btu/hr-ft^2
Furnace Liberation	37,000 Btu/hr-ft^3
EMISSION CONTROL EQUIPMENT:	Mechanical Collector

TABLE 5-3

EQUIPMENT DATA
TEST SITE: L3

BOILER:

Year Built	1951
Configuration	Multiple Pass
Rated Steaming Capacity	23,300 lb/hr (31,000 lb/hr peak)
Design Pressure	Unknown
Actual Operating Pressure	120 psig
Feedwater Temperature	212°F
Steam Temperature	Saturated
Operating Air Temperature	Ambient

STOKER:

Classification	Single Retort Underfeed
Effective Length	Unknown
Width	Unknown
Effective Grate Area	73.0 Ft^2

HEATING SURFACES:

Furnace Volume	Unknown
Water Wall	Unknown
Boiler	4,490 Ft^2
Superheater	None
Economizer	None
Air Heater	None

HEAT RATES AT RATED CAPACITY:

Input to Furnace	40,700,000 Btu/hr
Grate Width Heat Release	Unknown
Grate Heat Release	558,000 Btu/hr-ft^2
Furnace Liberation	Unknown

EMISSION CONTROL EQUIPMENT:	None

TABLE 5-4

EQUIPMENT DATA
TEST SITE: L5

BOILER:	
Year Built	1950
Configuration	Multiple Pass
Rated Steaming Capacity	28,460 lb/hr (37,950 lb/hr peak)
Design Pressure	Unknown
Actual Operating Pressure	150 psig
Feedwater Temperature	212°F
Steam Temperature	Saturated
Operating Air Temperature	Ambient
STOKER:	
Classification	Multiple Retort Underfeed
Effective Length	Unknown
Width	Unknown
Effective Grate Area	80.6 Ft^2
HEATING SURFACES:	
Furnace Volume	1,250 Ft^3
Water Wall	1,050 Ft^2
Boiler	4,440 Ft^2
Superheater	None
Economizer	None
Air Heater	None
HEAT RATES AT RATED CAPACITY:	
Input to Furnace	50,000,000 Btu/hr
Grate Width Heat Release	Unknown
Grate Heat Release	620,000 Btu/hr-ft^2
Furnace Liberation	40,000 Btu/hr-ft^3
EMISSION CONTROL EQUIPMENT:	None

TABLE 5-5

EQUIPMENT DATA
TEST SITE: L6

BOILER:

Year Built	1957
Configuration	Multiple Pass
Rated Steaming Capacity	20,000 lb/hr (27,000 lb/hr peak)
Design Pressure	Unknown
Actual Operating Pressure	110 psig
Feedwater Temperature	212°F
Steam Temperature	Saturated
Operating Air Temperature	Ambient

STOKER:

Classification	Multiple Retort Underfeed
Effective Length	Unknown
Width	Unknown
Effective Grate Area	83.3 Ft^2

HEATING SURFACES:

Furnace Volume	1,130 Ft^3
Water Wall	720 Ft^2
Boiler	3,280 Ft^2
Superheater	None
Economizer	None
Air Heater	None

HEAT RATES AT RATED CAPACITY:

Input to Furnace	33,900,000 Btu/hr
Grate Width Heat Release	Unknown
Grate Heat Release	407,000 Btu/hr-ft^2
Furnace Liberation	30,000 Btu/hr-ft^3

EMISSION CONTROL EQUIPMENT: None

TABLE 5-6

EQUIPMENT DATA
TEST SITE: L7

BOILER:

Year Built	1968
Configuration	Multiple Pass
Rated Steaming Capacity	50,000 lb/hr (55,000 lb/hr peak)
Design Pressure	Unknown
Actual Operating Pressure	150 psig
Feedwater Temperature	218°F
Steam Temperature	Saturated
Operating Air Temperature	Ambient

STOKER:

Classification	Multiple Retort Underfeed
Effective Length	Unknown
Width	Unknown
Effective Grate Area	161.1 Ft^2

HEATING SURFACES:

Furnace Volume	2,300 Ft^3
Water Wall	1,503 Ft^2
Boiler	6,057 Ft^2
Superheater	None
Economizer	None
Air Heater	None

HEAT RATES AT RATED CAPACITY:

Input to Furnace	76,360,000 Btu/hr
Grate Width Heat Release	Unknown
Grate Heat Release	474,000 Btu/hr-ft^2
Furnace Liberation	33,200 Btu/hr-ft^3

EMISSION CONTROL EQUIPMENT:	Mechanical Collector

TABLE 5-7

COAL IDENTIFICATION AND CLASSIFICATION*
MASS FIRED UNDERFEED STOKERS

Site	Identification	ASTM Classification	Fixed Carbon Dry Mineral Matter-Free Basis	Volatile Matter Dry Mineral Matter-Free Basis	Calorific Value Moist Mineral Matter-Free Basis
L1	C and C	High Volatile A Bituminous	64	36	15,360
L3	McIntire	High Volatile A Bituminous	54	46	15,260
L5	Glessner	Low Volatile Bituminous	80	20	15,600
L6	McIntire	High Volatile A Bituminous	64	36	15,360
L7	McIntire	High Volatile A Bituminous	64	36	15,090

*Classification of coals is by rank (ASTM D388) using the Parr Formulas

TABLE 5-8

PROXIMATE COAL ANALYSIS
MASS FIRED UNDERFEED STOKERS

	WEIGHT PERCENT AS-FIRED					
	Inherent Moisture	Ash	Volatile	Fixed Carbon	Btu/lb	Percent Sulfur
Site L1	.8	13.0	32.0	54.2	13,100	3.0
Site L3	.6	11.0	41.4	47.0	13,400	1.3
Site L5	.4	12.0	18.9	68.7	13,500	2.1
Site L6	.6	12.7	32.0	54.7	13,200	1.6
Site L7	.7	12.5	32.2	54.6	13,000	1.7

TABLE 5-9

ASH SOFTENING TEMPERATURE AND FREE SWELLING INDEX MASS FIRED UNDERFEED STOKERS

	Ash Softening Temperature	Free Swelling Index
Site L1	2550°F	6.0
Site L3	2650	6.0
Site L5	2450	8.0
Site L6	2550	7.5
Site L7	2550	7.5

TABLE 5-10

AS-FIRED COAL SIZE CONSISTENCY MASS FIRED UNDERFEED STOKERS

	Percent Passing Stated Screen Size				
	1-1/2"	3/4"	1/2"	1/4"	#16
Site L5	97	59	36	20	11
Site L6	89	24	15	9	5
Site L7	95	34	18	11	2

5.3 TEST CONDITIONS

Each of the five underfeed stokers was tested under a single operating condition. Test dates were selected to obtain loads in the range of 55% to 100% of design capacity. This corresponds to a maximum steaming capacity range of 50% to 75%. Each boiler was tested under normal operating conditions at the available load. The boiler firing conditions are summarized in Table 5-11.

TABLE 5-11

BOILER FIRING CONDITIONS

	% Design Capacity	% Maximum Capacity	% Excess Air	Grate Heat Release 10^3Btu/hr-ft^2	Furnace Heat Release 10^3Btu/hr-ft^3
Site L1	100	75	71	412	32.7
Site L3	80	60	186	272	Not Available
Site L5	73	55	33	348	22.4
Site L6	88	65	61	315	23.3
Site L7	55	50	116	264	18.5

5.4 PARTICULATE EMISSION LEVELS

The particulate emission levels of the five underfeed stokers are presented in Table 5-12. On the three units without dust collectors, uncontrolled particulate loadings ranged from .25 to .71 lb/10^6Btu. On the two units with mechanical collectors, the controlled particulate loadings were .46 and .58 lb/10^6Btu.

TABLE 5-12

PARTICULATE LOADING DATA FOR FIVE UNDERFEED STOKERS

	PARTICULATE LOADING $lb/10^6Btu$		% Excess	Stack Velocity	% Fines
	Uncontrolled	Controlled	Air	ft/sec	<¼"
Site L1	No Data	.456	71	51.0	No Data
Site L3	.709	No Collector	186	11.6	No Data
Site L5	.249	No Collector	33	3.8	20
Site L6	.403	No Collector	61	5.0	9
Site L7	No Data	.577	116	49.5	11

The most surprising result is that emissions from those units equipped with dust collectors were no lower than from those without. In fact, if we overlook site L3 because it is the only single retort stoker, we see that the stokers with dust collectors had higher stack emissions than those without.

Two factors which may have contributed to this result are particle size distribution and stack gas velocity. The particles at the boiler outlet were very fine; 45% smaller than 10 micrometers and 57% smaller than 20 micrometers at Site L7 based on cascade impactor data. Particles of this size are not efficiently collected by mechanical dust collectors. It is also noted that the three units without dust collectors had tall, large diameter stacks which resulted in low stack velocities. These low velocities could allow much of the particulate matter to settle out before leaving the stack, thus providing some degree of particulate control.

The variation in particulate loadings among the three underfeed stokers not equipped with dust collectors could be explained by a number of factors. It is noted in Table 5-12 that the particulate loadings at Sites L3, L5 and L6 are proportional to both excess air level and stack gas velocity. It is also noted that the highest particulate loading occurred while firing the coal with the lowest volatiles and the highest free swelling index, and it occurred in the only single retort stoker tested.

Several other variables also correlate with particulate loading. However, it is clear that there are more variables here than there are test sites. Therefore, it is impossible to identify which variables had the strongest effect on emissions. The underfeed stoker study was not designed or intended to accomplish this task.

Table 5-12 gave the measured particulate loading data for the five underfeed stokers. Uncontrolled particulate emissions were not measured at Sites L1 and L5, the two sites equipped with mechanical collectors. To provide a means of comparing uncontrolled emission rates at all sites, uncontrolled particulate emissions from Sites L1 and L7 were calculated by applying collector efficiency data derived from particle size distribution test results. This method, discussed in more detail in Section 5.6 Particle Size Distribution and Dust Collector Efficiency, yields uncontrolled particulate loadings of .684 lb/10^6Btu for Site L1 and 1.464 lb/10^6Btu for Site L7.

Emission factors were determined for the five underfeed stokers. The particulate emission factor for coal combustion without control devices for all stoker types except spreaders, as reported in the U.S. Environmental Protective Agency Publication AP-42, Compilation of Air Pollution Factors, Third Edition, is 5A (potential emission rate in pounds of particulate per ton of coal fired is equal to five times the weight percentage of ash in the coal). The uncontrolled emission rates were converted to equivalent particulate emission factors provided by this publication. A summary of the calculated factors are listed in Table 5-13. These data indicate that emissions were considerably lower than those predicted by AP-42.

TABLE 5-13

PARTICULATE EMISSION FACTORS LB/TON
MASS FIRED UNDERFEED STOKERS

	By Test Emission Rates	By Calculated Emission Rates		
		Average	High	Low
Site L1	--	1.4A	1.4A	1.3A
Site L3	1.7A	--	--	--
Site L5	0.6A	--	--	--
Site L6	0.8A	--	--	--
Site L7	--	3.0A	3.6A	2.1A
AP 42	5A			

5.5 COMBUSTIBLES IN THE ASH

The combustible fraction of the bottom ash was determined for each site. The data, shown in Table 5-14, indicate that four of the sites had nearly identical combustible fractions ranging from 22.4% to 25.0%. One site had only 8.1% combustibles in its bottom ash. No explanation was found for this low value, but it is noted that variations of this magnitude were not uncommon at some of the other test sites in this program. See for example Figures 3-13 and 4-12 in Sections 3.2 and 4.2 of this report.

TABLE 5-14

COMBUSTIBLES IN THE ASH
MASS FIRED UNDERFEED STOKERS

	% Combustibles In Bottom Ash	% Combustibles In Flyash
Site L1	22.4	20.5
Site L3	25.0	No Data
Site L5	22.5	No Data
Site L6	8.1	No Data
Site L7	22.4	20.2

The combustible fraction of the flyash was determined from samples collected at the base of the mechanical collector at the two sites which had mechanical collectors. The combustible fractions were very similar at 20.5% and 20.2% for Sites L1 and L7, respectively.

5.6 BOILER EFFICIENCY

Boiler efficiencies were not an objective of the test program on the underfeed stokers. However, sufficient data were generated to calculate boiler efficiency by the heat loss method (ASME PTC 4.1). The heat loss and boiler efficiency data are listed in Table 5-15. Heat losses are bracketed where major assumptions were required.

TABLE 5-15

HEAT LOSSES AND EFFICIENCIES
MASS FIRED UNDERFEED STOKERS

Site	Dry Gas	Moisture In Fuel	Hydrogen In Fuel	Flyash Combustibles	Bottom Ash Combustibles	Radiation	Other	BOILER EFFICIENCY
L1	15.11	.08	(4.36)	.13	3.93	.75	1.50	74.14
L3	25.34	.06	(4.14)	(.21)	3.64	.98	1.50	64.13
L5	15.03	.04	(4.13)	(.07)	3.59	.97	1.50	74.67
L6	15.19	.06	(4.19)	(.11)	1.17	.97	1.50	76.81
L7	21.09	.07	(4.45)	.17	3.76	.97	1.50	68.01

Among the assumptions were the following. Combustibles in the flyash of Sites L3, L5 and L6 were assumed to be 21%. Combustible material was assumed to have a heating value of 14,500 Btu/lb. Combustion air temperature was assumed to be 80°F. Because only proximate fuel analysis were obtained, fuel hydrogen was assumed to be 5% and fuel carbon was calculated as percent fixed carbon + .6 (percent volatiles). This empirical formula is based on eleven proximate and ultimate fuel analysis from Sites D, H, I, J and K which yielded a factor of .606±.032 as the fraction of carbon in the volatile material.

Finally, it should be noted that the heat loss due to moisture in the fuel is based on inherent moisture only. Surface moisture would be expected to add about .10% to this heat loss.

Despite the many assumptions, the boiler efficiencies are thought to be accurate within ±1%. The lowest boiler efficiency, Site L3, resulted from excessively high excess air. The second lowest, Site L7, resulted from a combination of high excess air and high stack gas temperature.

5.7 PARTICLE SIZE DISTRIBUTION OF THE FLYASH

Particle size information was obtained from the mass fired underfeed stokers with an Anderson in-stack cascade impactor, and with a Bahco centrifugal classifier.

The boiler outlet sizing data are displayed on log probability plots in Figures 5-2 and 5-3. The stack data are similarly displayed in Figures 5-4 and 5-5. The log probability plot is useful in that one can determine the percentage of particles smaller than any given size.

Table 5-16 gives the average and standard deviation of the size distribution data at selected points. This allows for a convenient comparison with the size distribution data obtained on the overfeed stokers and the spreader stokers. Because of the relatively wide variations in magnitude and the few data points included, these averages should be seen for what they are and used accordingly.

TABLE 5-16

AVERAGE SIZE DISTRIBUTION DATA FOR UNDERFEED STOKERS

	Mass Percent Smaller Than Stated Size & Standard Deviation					
	.3μm	1μm	3μm	10μm	20μm	44μm
Boiler Outlet Impactor Data	11.7± 6.6	23.5±18.0	29.5±20.0	44.3±21.4	59.4±20.1	71.8±12.2
Boiler Outlet Bahco Data	--	--	9.3± 3.5	22.7± 8.9	32.7±12.1	46.4±16.6
Collector Outlet Impactor Data*	11.0-20.0	18.8-34.2	29.0-51.3	50.0-82.5	78.2-95.6	85.3-95.6
Collector Outlet Bahco Data*	--	--	14.2-35.7	48.0-50.0	51.2-71.5	54.7-87.3

*Since only two of the units had collectors, the actual collector outlet data are shown for each test rather than the average and standard deviation.

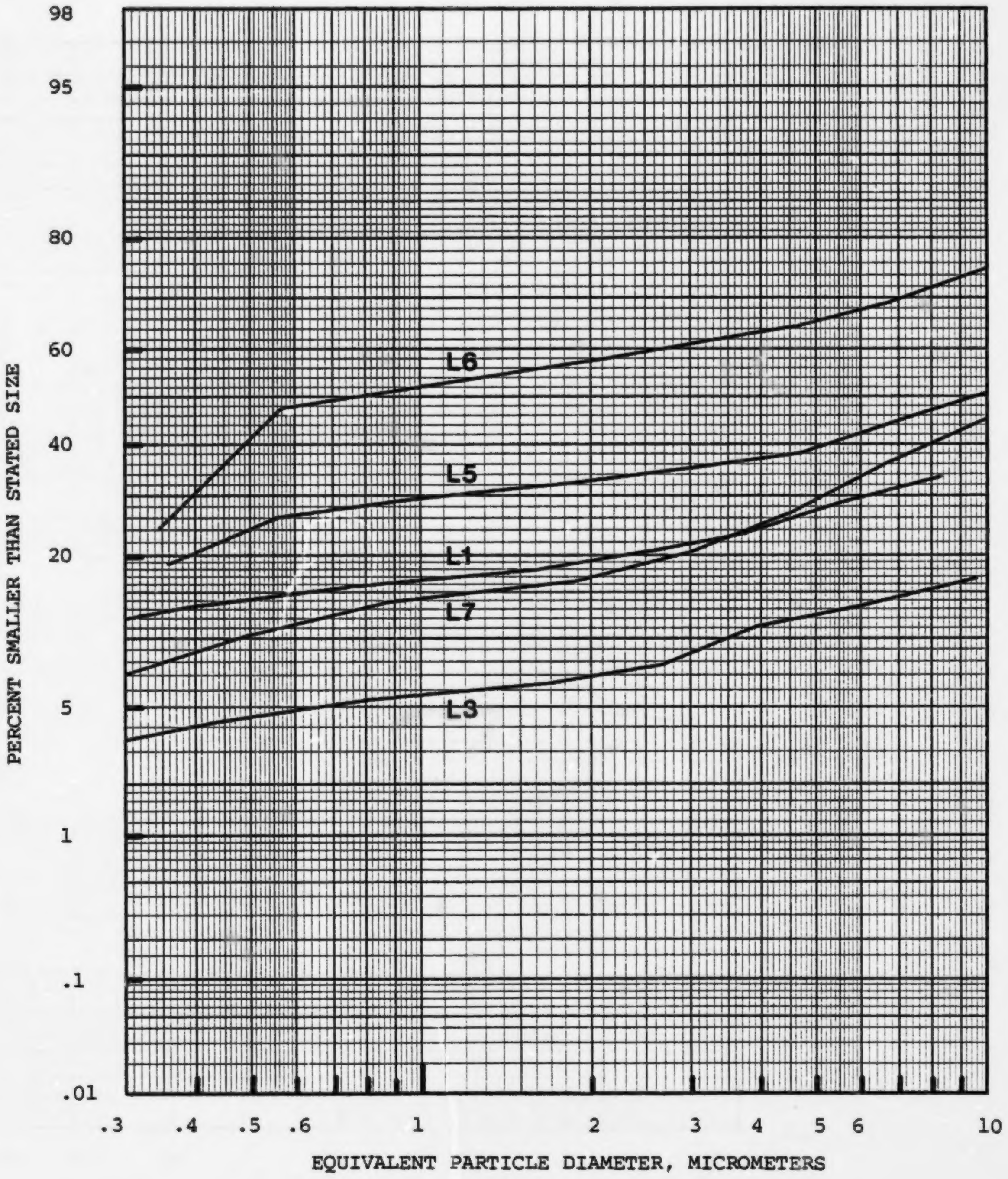


Figure 5-2. Particle Size Distribution at the Boiler Outlet of Five Underfeed Stokers as Determined by Cascade Impactor.

KVB4-15900-554

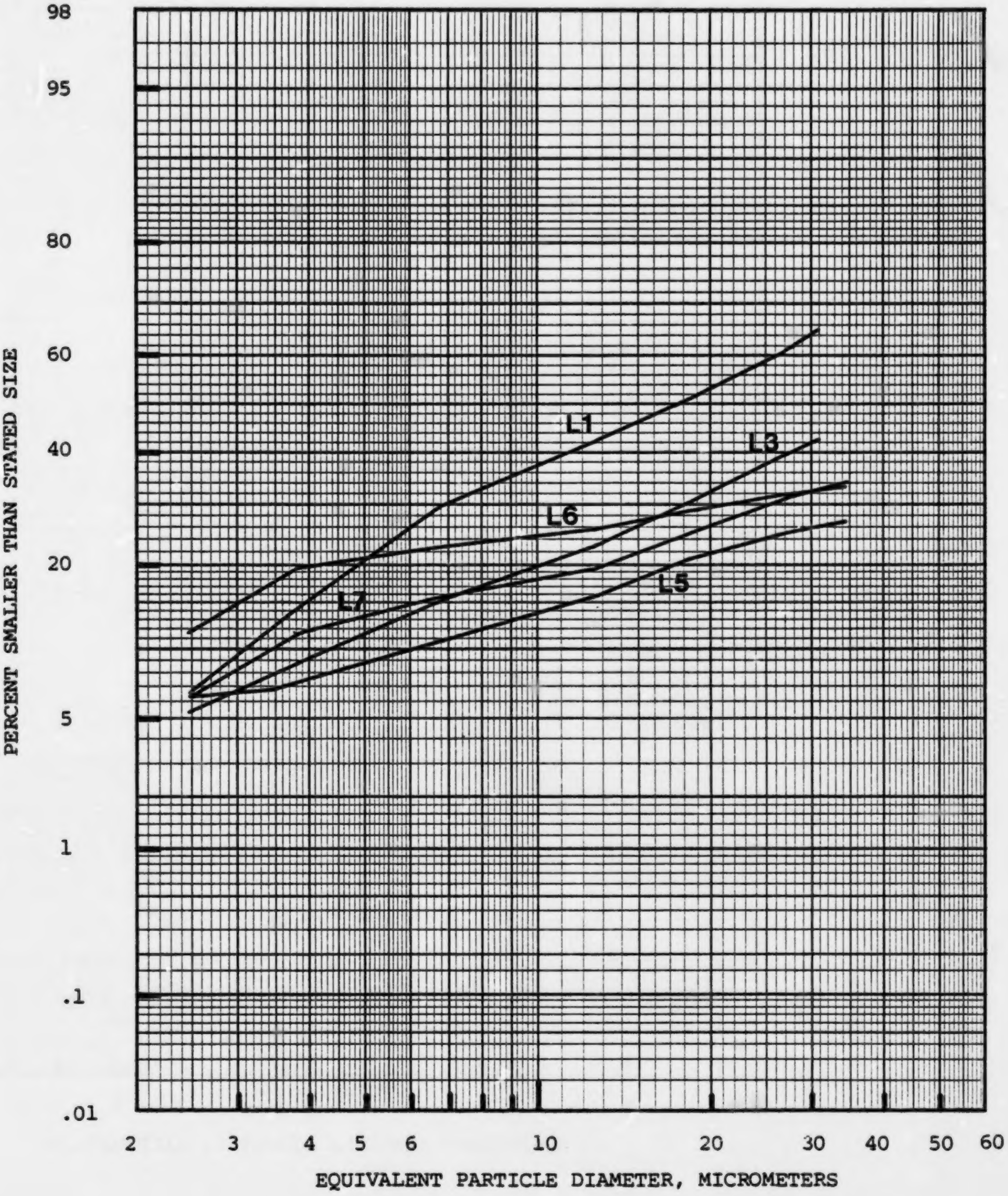


Figure 5-3. Particle Size Distribution at the Boiler Outlet of Five Underfeed Stokers as Determined by Bahco Classifier.

KVB4-15900-554

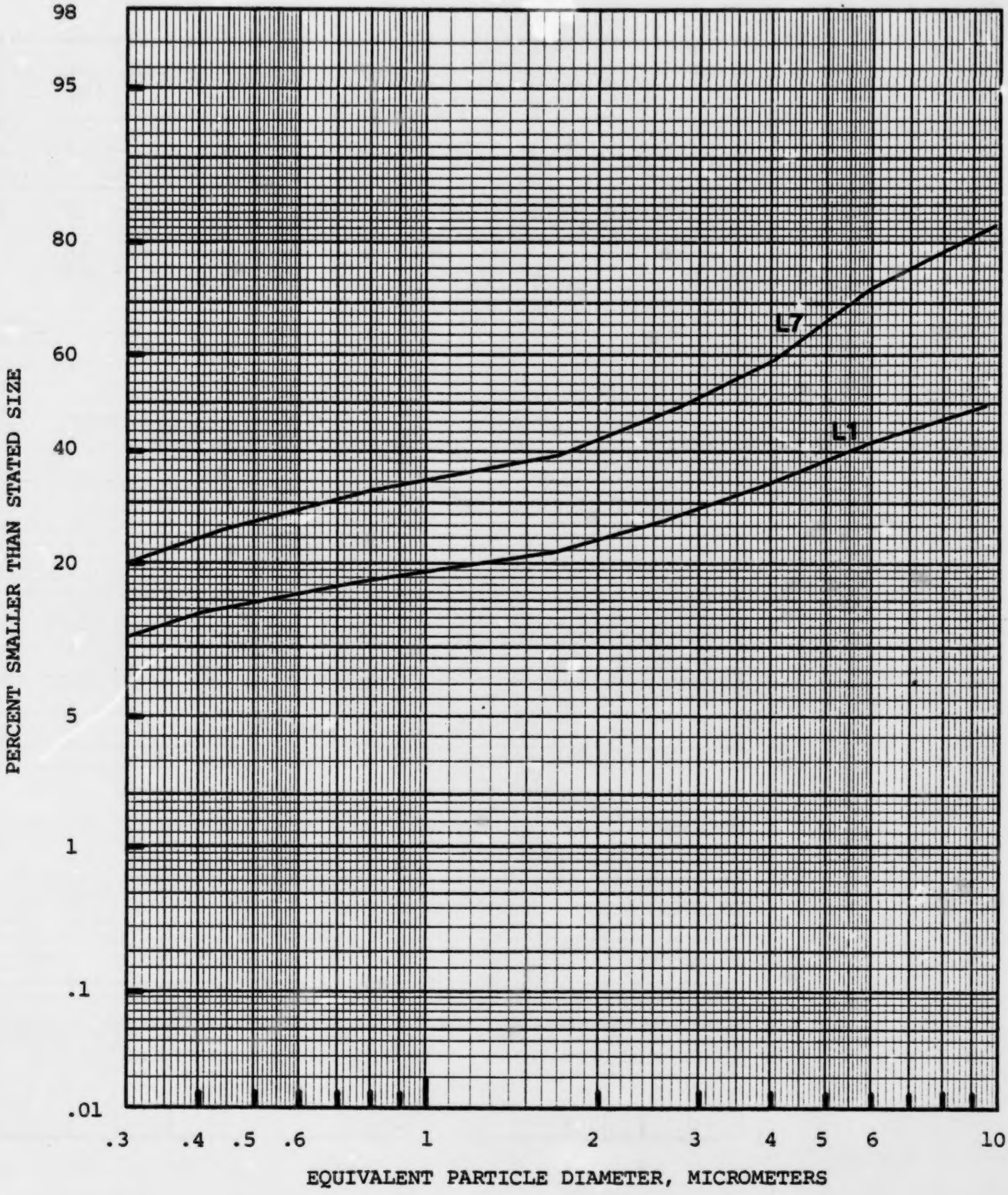


Figure 5-4. Particle Size Distribution Downstream of the Mechanical Collector on Two Underfeed Stokers as Determined by Cascade Impactor.

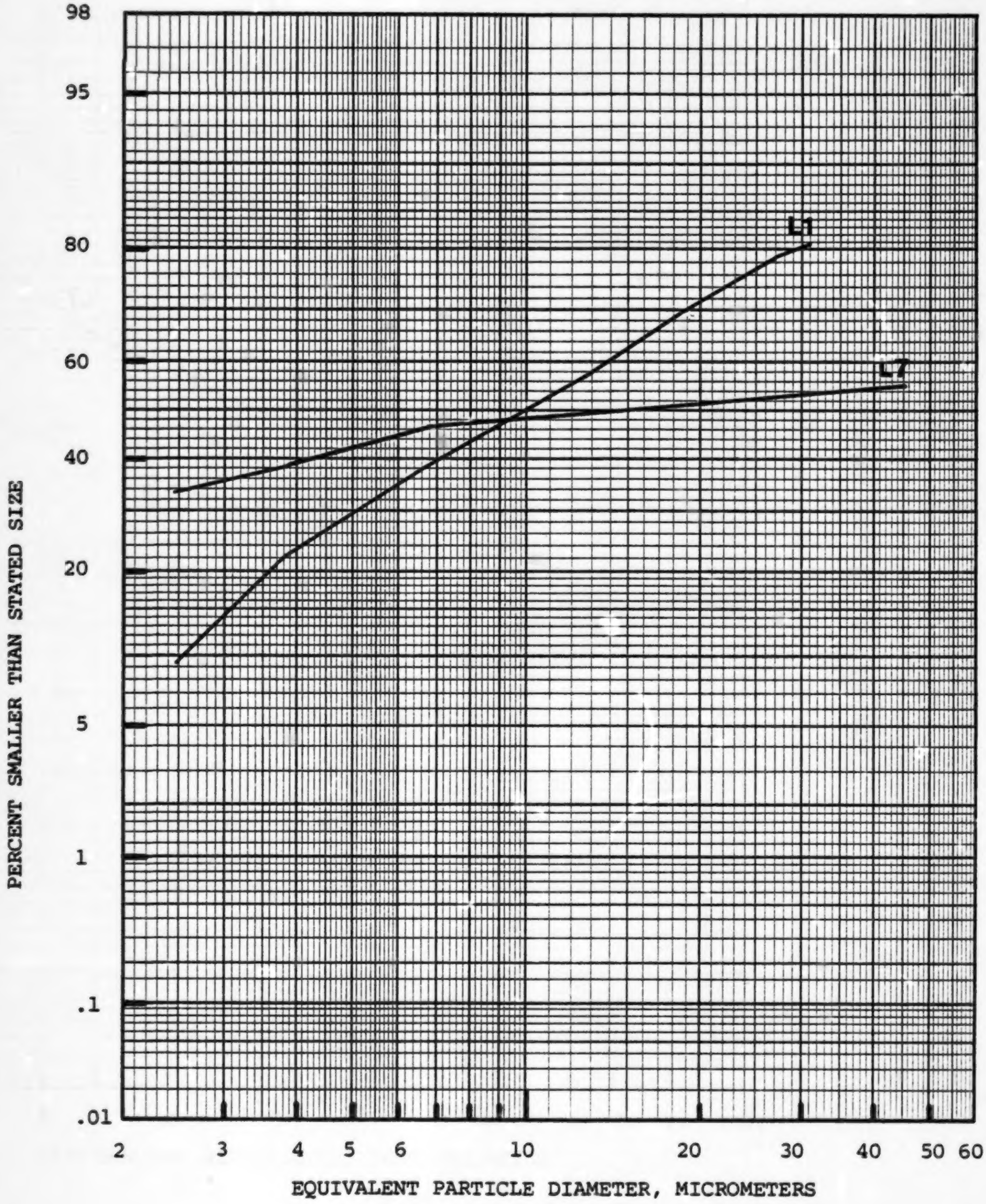


Figure 5-5. Particle Size Distribution Downstream of the Mechanical Collector on Two Underfeed Stokers as Determined by Bahco Classifier.

Dust collector efficiency with respect to particle size was calculated from impactor size distribution data obtained at the inlet and outlet of the dust collectors at Site L1 and L7. The results are summarized in Table 5-17. It is noted that the collector at Site L1 was operating at 80% of its design flowrate, while the collector at Site L7 was operating at 95% of its design flowrate.

TABLE 5-17

EFFICIENCY WITH RESPECT TO PARTICLE SIZE

Particle Size Ranges Micrometers	Collector Efficiency	
	Site L1	Site L7
125 - 30	72	93
30 - 20	74	74
20 - 10	14	69
10 - 1	0.4	57
Overall Efficiency	37	66

6.0 TEST EQUIPMENT AND PROCEDURES FOR SITES A THROUGH K

This section describes the test equipment used and the sampling procedures followed to obtain accurate and representative data at Test Site A through K. The test equipment and procedures used for Test Site L1 through L7 are described in Section 7.0.

6.1 GASEOUS EMISSIONS MEASUREMENTS

Gaseous emission measurements were made with analytical instrumentation and by wet chemical methods to determine emission concentrations of oxides of nitrogen (NO, NOx), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), gaseous hydrocarbons (HC), and oxides of sulfur (SO_2, SO_3).

6.1.1 Analytical Instruments and Related Equipment

A description is given below of the analytical instrumentation, related equipment, and the gas sampling and conditioning system, all of which are located in a mobile testing van owned and operated by KVB. The systems have been developed as a result of testing since 1970, and are operational and fully checked out.

The analytical system consists of six instruments and associated equipment for simultaneously measuring the constituents of flue gas. The analyzers, recorders, valves, controls, and manifolds are mounted on a panel in the vehicle. The analyzers are shock mounted to prevent vibration damage. The flue gas constituents which are measured are oxides of nitrogen (NO, NOx), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), gaseous hydrocarbons (HC), and sulfur dioxide (SO_2).

The gas sampling and conditioning system consists of probes, sample lines, valves, pumps, filters and other components necessary to deliver a representative, conditioned sample gas to the analytical instrumentation. The entire gas sampling and conditioning system shown schematically in Figure 6-1 is contained in the emission test vehicle. A slightly different test vehicle was used

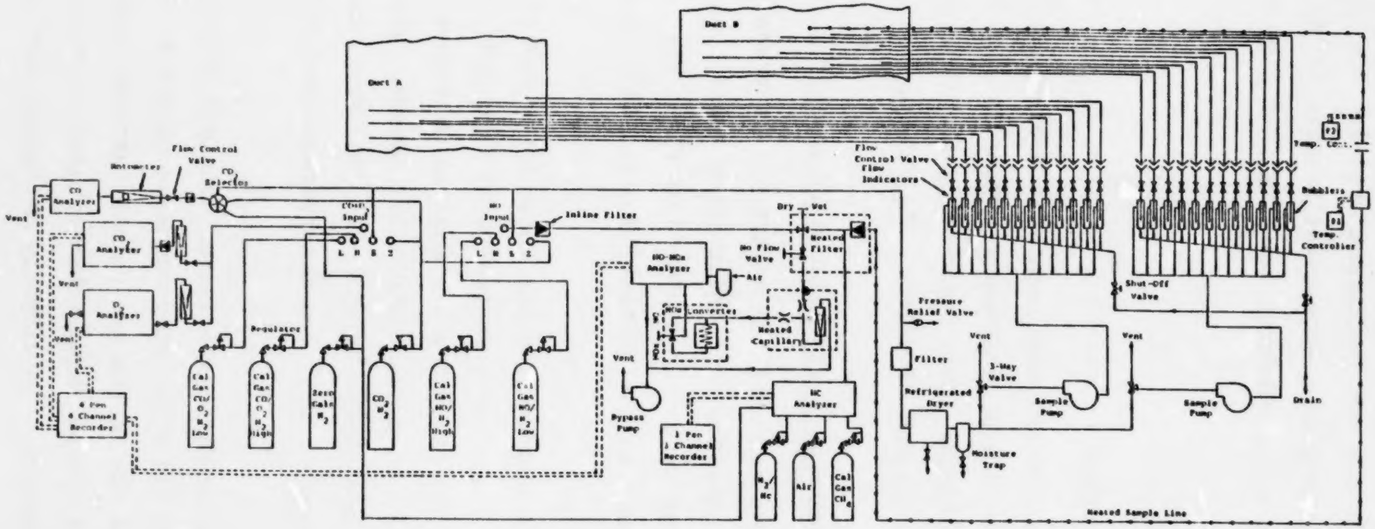

Duct A
Duct B
Vent
CO Analyzer
Rotometer
Flow Control Valve
CO Selector
CO_2 Analyzer
Vent
O_2 Analyzer
Vent
4 Pen 4 Channel Recorder
Regulator
Cal Gas CO/ O_2 N_2 Low
Cal Gas CO/ O_2 N_2 High
Zero Gas N_2
CO_2 N_2
Cal Gas NO/ N_2 High
Cal Gas NO/ N_2 Low
CO_2 Input
L H S Z
NO Input
L H S Z
Inline Filter
NO-NOx Analyzer
Air
NOx Converter
Vent
Bypass Pump
1 Pen 1 Channel Recorder
HC Analyzer
N_2/ He
Air
Cal Gas CH_4
Dry
Wet
Heated Filter
No Flow Valve
Heated Capillary
Flow Control Valve
Flow Indicators
Pressure Relief Valve
Filter
Refrigerated Dryer
Moisture Trap
Vent
3-Way Valve
Sample Pump
Shut-Off Valve
Vent
Sample Pump
Drain
Steam
Temp. Cont.
Bubblers
Temp. Controller
Heated Sample Line

Figure 6-1. Flow Schematic of Mobile Flue Gas Monitoring Laboratory

at Test Sites F and H. All the analytical instruments contained in this test vehicle were the same, with the addition of an SO_2 analyzer.

Boiler access points for gaseous sampling were selected in the same sample plane as were particulate sample points. Each probe consisted of one-half inch 316 stainless steel heavy wall tubing. A 100 micrometer Mott Metallurgical Corporation sintered stainless steel filter was attached to each probe for removal of particulate material.

Gas samples to be analyzed for O_2, CO_2, CO and NO were conveyed to the KVB mobile laboratory through 3/8 inch nylon sample lines. After passing through bubblers for flow control, the samples passed through a diaphragm pump and a refrigerated dryer to reduce the sample dew point temperature to 35°F. After the dryer, the sample gas was split between the various continuous gas monitors for analysis. Flow through each continuous monitor is accurately controlled with rotometers. Excess flow is vented to the outside. Gas samples may be drawn both individually and/or compositely from all probes during each test.

A detailed discussion of each analytical instrument follows:

Oxides of Nitrogen. The instrument used to monitor oxides of nitrogen was a Thermo Electron Model 10 chemiluminescent nitric oxide analyzer. The instrument operates by measuring the chemiluminescent reaction of NO and O_3 to form NO_2. Light is emitted when electronically excited NO_2 molecules revert to their ground state. The resulting chemiluminescence is monitored through an optical filter by a high sensitivity photomultiplier, the output of which is linearly proportional to the NO concentration.

Air for the ozonator is drawn from ambient air through a dryer and a ten-micrometer filter element. Flow control for the instrument is accomplished by means of a small bellows pump mounted on the vent of the instrument downstream of a separator that prevents water from collecting in the pump.

The basic analyzer is sensitive only to NO molecules. To measure NOx (i.e., $NO+NO_2$), the NO_2 is first converted to NO. This is accomplished by a converter which is included with the analyzer. The conversion occurs as the gas passes through a thermally insulated, resistance heated, stainless steel coil. With the application of heat, NO_2 molecules in the sample gas are reduced to NO molecules, and the analyzer now reads NOx. NO_2 is obtained by the difference in readings obtained with and without the converter in operation.

Specifications:
- Accuracy 1% of full scale
- Span stability ±1% of full scale in 24 hours
- Zero stability ±1 ppm in 24 hours
- Power requirements 115±10V, 60 Hz, 1000 watts
- Response 90% of full scale in 1 sec. (NOx mode), 0.7 sec. NO mode
- Output 4-20 ma
- Sensitivity 0.5 ppm
- Linearity ±1% of full scale
- Vacuum detector operation
- Ranges: 2.5, 10, 25, 100, 250, 1000, 2500 and 10,000 ppm full scale

Carbon Monoxide. Carbon monoxide concentration was measured by a Beckman 315B non-dispersive infrared analyzer at Sites A through F and H. A Series Five Model AB non-dispersive infrared analyzer made by Sensor, Inc. was used at Site K. These instruments measure the differential in infrared energy absorbed from energy beams passed through a reference cell (containing a gas selected to have minimal absorption of infrared energy in the wavelength absorbed by the gas component of interest) and a sample cell through which the sample gas flows continuously. For the Beckman instrument the differential absorption appears as a reading on a scale from 0 to 100 and is then related to the concentration of the species of interest by calibration curves supplied with the instrument. Carbon monoxide concentrations from the Sensors instrument are read directly in parts per million.

Beckman Specifications:
- Span stability ±1% of full scale in 24 hours
- Zero stability ±1% of full scale in 24 hours
- Ambient temperature range 32°F to 120°F
- Line voltage 115±15V rms
- Response 90% of full scale in 0.5 or 2.5 sec.
- Precision ±1% of full scale
- Output 4-20 ma
- Ranges: 0-500 ppm and 0-2000 ppm

Sensor Specifications:
- Linearity 2.6% full scale
- Span stability ±1% of full scale in 24 hours
- Zero stability ±1% of full scale in 24 hours
- Ambient temperature range 32°F to 120°F
- Line voltage 115±15V rms

Response: 90% of full scale in 0.5 or 2.5 sec
Precision: ±1% of full scale
Output: 0-1 volt
Ranges: 0-500 ppm and 0-1000 ppm

Carbon Dioxide. Carbon dioxide concentration was measured by a Beckman Model 864 short path-length, non-dispersive infrared analyzer. This instrument measures the differential in infrared energy absorbed from energy beams passed through a reference cell (containing a gas selected to have minimal absorption of infrared energy in the wavelength absorbed by the gas component of interest) and a sample cell through which the sample gas flows continuously. The differential absorption appears as a reading on a scale from 0 to 100 and is then related to the concentration of the specie of interest by calibration curves supplied with the instrument.

Specifications: Span stability ±1% of full scale in 24 hours
Zero stability ±1% of full scale in 24 hours
Ambient temperature range 32°F to 120°F
Line voltage 115±15V rms
Response 90% of full scale in 0.5 or 2.5 sec.
Precision ±1% of full scale
Output 4-20 ma
Ranges: 0-5% and 0-20%

Oxygen. The oxygen content of the flue gas sample was automatically and continuously determined with a Teledyne Model 326A Oxygen analyzer. With this instrument, oxygen in the flue gas diffuses through a Teflon membrane and is reduced on the surface of the cathode. A corresponding oxidation occurs at the anode internally and an electric current is produced that is proportional to the concentration of oxygen. This current is measured and conditioned by the instrument's electronic circuitry to give a final output in percent O_2 by volume.

Specifications: Precision ±1% of full scale
Response 90% in less than 40 sec.
Sensitivity 1% of low range
Linearity ±1% of full scale
Ambient temperature range 32-125°F
Fuel cell life expectancy 40,000%-hours
Power requirement 115 VAC, 50-60 Hz, 100 watts
Output 4-20 ma
Ranges: 0-5%, 0-10%, and 0-25%

Hydrocarbons. Hydrocarbons were measured using a Beckman Model 402 hydrocarbon analyzer which utilizes the flame ionization method of detection. The sample for this instrument was drawn to the analyzer through a heated line to prevent the loss of higher molecular weight hydrocarbons. It was then filtered and supplied to the burner by means of a pump flow control system. The sensor, which is the burner, has its flame sustained by regulated flows of fuel (40% hydrogen plus 60% helium) and air. In the flame, the hydrocarbon components of the sample undergo a complete ionization that produces electrons and positive ions. Polarized electrodes collect these ions, causing a small current to flow through a circuit. This ionization current is proportional to the concentration of hydrocarbon atoms which enter the burner.

Specifications: Full scale sensitivity, adjustable from 5 ppm CH_4 to 10% CH_4

Ranges: Range multiplier switch has 8 positions: X1, X5, X10, X50, X100, X500, X1000, and X5000. In addition, span control provides continuously variable adjustment within a dynamic range of 10:1

Response time 90% full scale in 0.5 sec.

Precision ±1% of full scale

Electronic stability ±1% of full scale for successive identical samples

Reproducibility ±1% of full scale for successive identical samples

Analysis temperature: ambient

Ambient temperature 32°F to 110°F

Output 4-20 ma

Air requirements 350 to 400 cc/min of clean, hydrocarbon-free air, supplied at 30 to 200 psig

Fuel gas requirements 75 to 80 cc/min of pre-mixed fuel consisting of 40% hydrogen and 60% nitrogen or helium, supplied at 30 to 200 psig

Electrical power requirements 120V, 60 Hz

Automatic flame-out indication and fuel shut-off valve

Sulfur Dioxide. Sulfur dioxide was measured at Sites F and H by a Dupont Model 400 photometric analyzer. This analyzer measures the difference in absorption of two distinct wavelengths (ultraviolet) by the sample. The radiation from a selected light source passes through the sample and then into the photometer unit where the radiation is split by a semi-transparent mirror into two beams. One beam is directed to a phototube through a filter which removes all wavelengths except the "measuring" wavelength which is strongly absorbed by the constituent in the sample. A second beam falls on a reference phototube, after passing through an optical filter which transmits only the "reference" wavelength. The latter is absorbed only weakly, or not at all, by the constituent in the sample cell. The phototubes translate these intensities to proportional electric currents in the amplifier. In the amplifier, full correction is made for the logarithmic relationships between the ratio of the intensities and concentration or thickness (in accordance with Beer's Law). The output is, therefore, linearly proportional, at all times, to the concentration and thickness of the sample.

Specifications: Noise less than 1/4%
Drift less than 1% full scale in 24 hours
Accuracy (±1% of analyzer reading)+(±1/4% of full scale range)
Sample cell 304 stainless steel, quartz windows
Flow rate 6 CFH
Light source is mercury vapor, tungsten, or "Osram" discharge type lamps
Power rating 500 watts maximum, 115V, 60 Hz
Reproducibility 1/4% of scale
Electronic response 90% in 1 sec.
Sample temperature 378 K (220°F)
Output 4-20 ma d.c.
Lower detection limit of 2 ppm
Ranges: 0-200 ppm and 0-2000 ppm

Recording Instruments. The output of the O_2, CO, CO_2 and NOx analyzers was displayed on front panel meters and was simultaneously recorded on a Texas Instrument Model FLO4W6D four-pen strip chart recorder. The recorder specifications are as follows:

Chart size 9-3/4 inch
Accuracy ±0.25%
Linearity <0.1%
Line voltage 120V±10% at 60 Hz
Span step response: one second

6.1.2 Wet Chemical Methods and Related Equipment

A description of the three wet chemical methods used to determine SO_2 and SO_3 emissions are given below. The Shell-Emeryville method was performed at all test sites except F and H during this test program. EPA Method 6 was used at Test Sites E, G, I, J and K in addition to and as a check with the Shell-Emeryville method. At Test Sites F and H the Dupont Model 400 photometric analyzer was used to determine SO_2 for all tests run. The Goksoyr-Ross controlled condensate method was then used for SO_3 emission determinations to supplement the data at these two sites.

Shell-Emeryville Method. The gas sample is drawn from the stack through a glass probe (Figure 6-2), containing a quartz wool filter to remove particulate matter, into a system of three sintered glass plate absorbers (Figure 6-3). The first two absorbers contain aqueous isopropyl alcohol and remove the sulfur trioxide; the third contains aqueous hydrogen peroxide solution which absorbs the sulfur dioxide. Some of the sulfur trioxide is removed by the first absorber, while the remainder, which passes through as sulfuric acid mist, is completely removed by the secondary absorber mounted above the first. After the gas sample has passed through the absorbers, the gas train is purged with nitrogen to transfer sulfur dioxide, which has dissolved in the first two absorbers, to the third absorber to complete the separation of the two components. The isopropyl alcohol is used to inhibit the oxidation of sulfur dioxide to sulfur trioxide before it gets to the third absorber.

The isopropyl alcohol absorber solutions are combined and the sulfate resulting from the sulfur trioxide absorption is titrated with standard lead perchlorate solution using Sulfonazo III indicator. In a similar manner, the hydrogen peroxide solution is titrated for the sulfurate resulting from the sulfur dioxide absorption.

The gas sample is drawn from the flue by a single probe made of quartz glass inserted into the duct approximately one-third to one-half way. The inlet end of the probe holds a quartz wool filter to remove particulate matter. It is important that the entire probe temperature be kept above the dew point of sulfuric acid during sampling (minimum temperature of 260°C). This is accomplished by wrapping the probe with a heating tape.

EPA Method 6. This alternative method for determining SO_2 (Figure 6-4), employs an impinger train consisting of a bubbler and three midget impingers. The bubbler contains isopropanol. The first and second impingers contain aqueous hydrogen peroxide. The third impinger is left dry. The quartz probe and filter used in the Shell-Emeryville method is also used in Method 6.

Method 6 differs from Shell-Emeryville in that Method 6 requires that the sample rate be proportional to stack gas velocity. Method 6 also differs from Shell-Emeryville in that the sample train in Method 6 is purged with am-

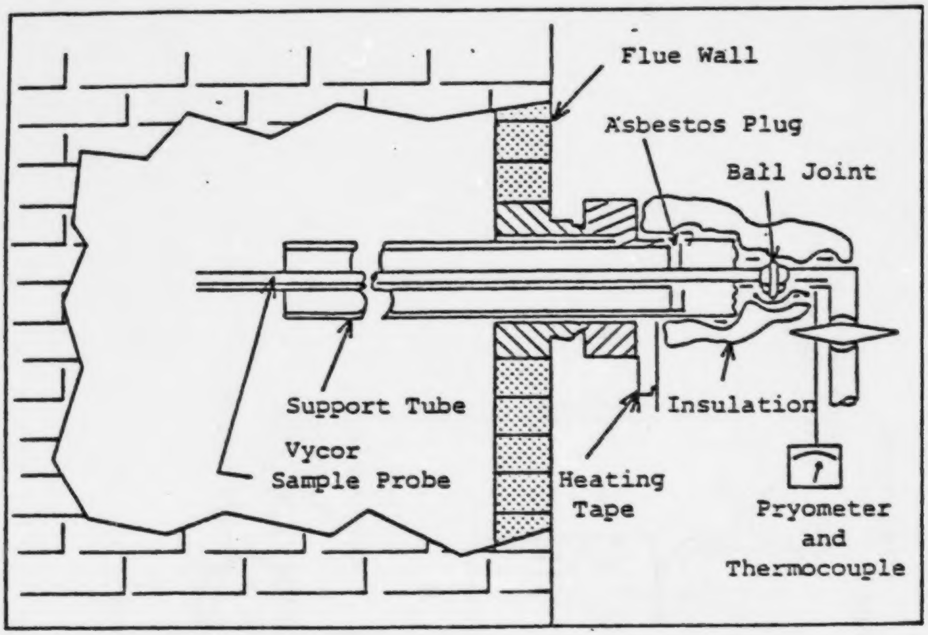

Flue Wall
Asbestos Plug
Ball Joint
Support Tube
Insulation
Vycor
Sample Probe
Heating
Tape
Pryometer
and
Thermocouple

Figure 6-2. SOx Sample Probe Construction

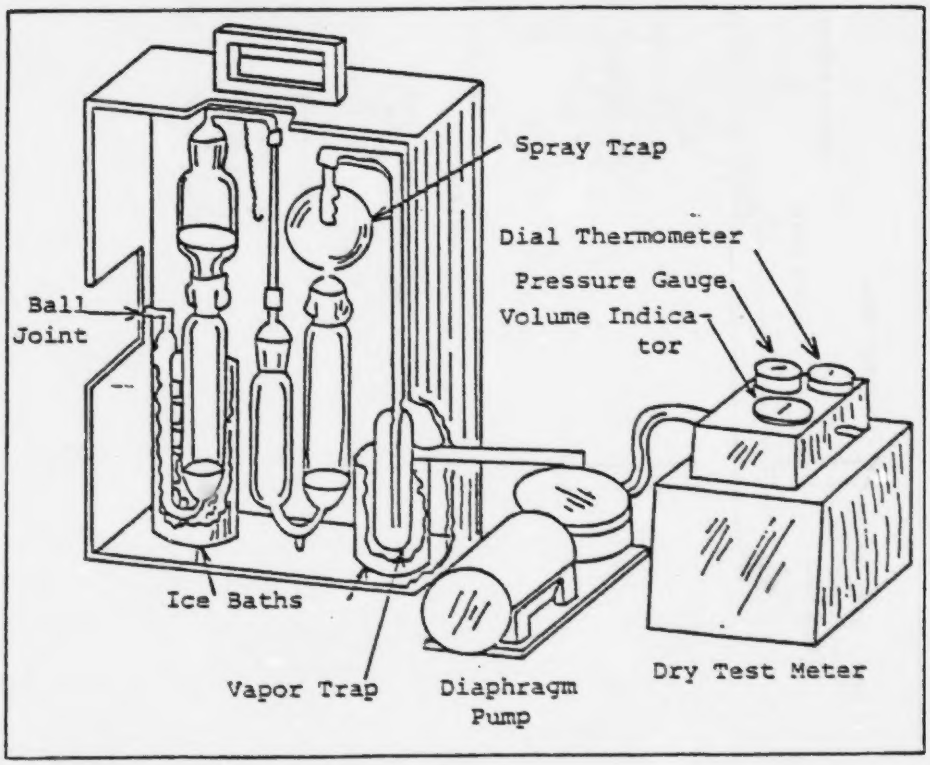

Spray Trap
Dial Thermometer
Pressure Gauge
Volume Indicator
Ball
Joint
Ice Baths
Vapor Trap
Diaphragm
Pump
Dry Test Meter

Figure 6-3. Shell-Emeryville Sulfur Oxides Sampling Train

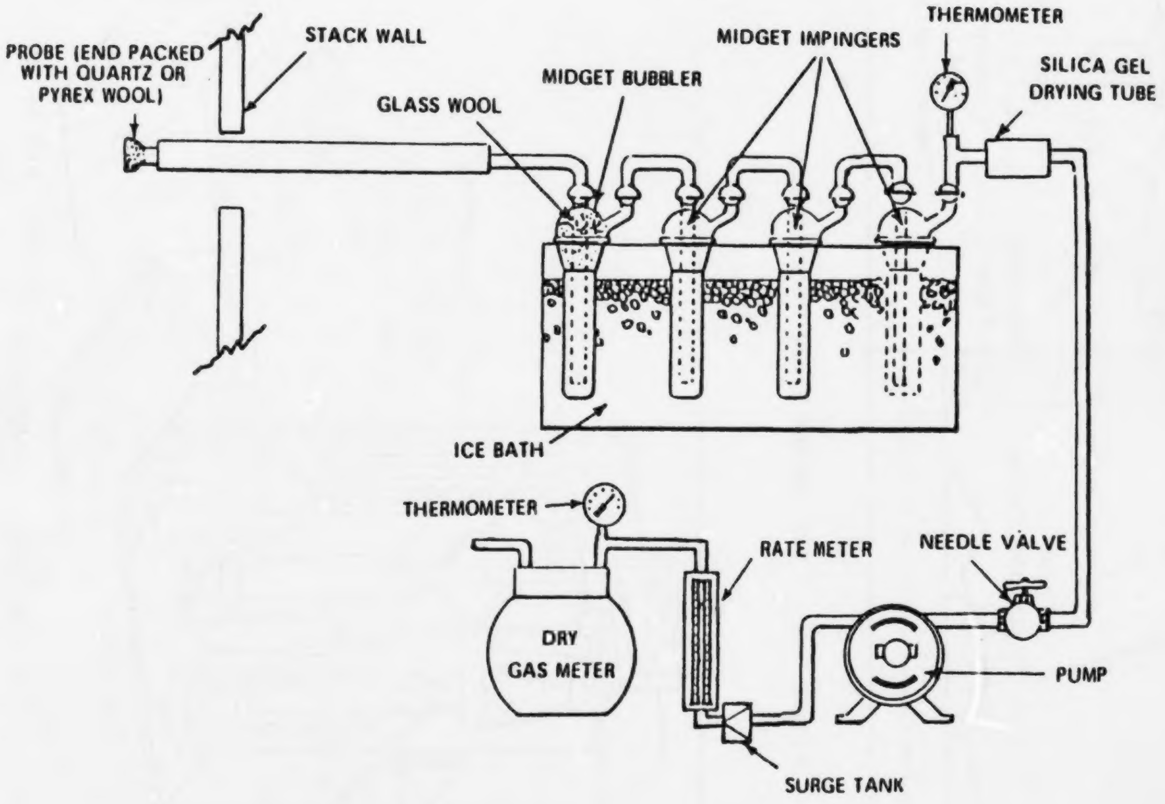

PROBE (END PACKED WITH QUARTZ OR PYREX WOOL)
STACK WALL
GLASS WOOL
MIDGET BUBBLER
MIDGET IMPINGERS
THERMOMETER
SILICA GEL DRYING TUBE
ICE BATH
THERMOMETER
RATE METER
NEEDLE VALVE
DRY GAS METER
PUMP
SURGE TANK

Figure 6-4. EPA Method 6 Sulfur Oxide Sampling Train

bient air, instead of nitrogen. Sample recovery involves combining the solutions from the first and second impingers. A 10 ml aliquot of this solution is then titrated with standardized barium perchlorate.

Two repetitions of Shell-Emeryville and two repetitions of EPA Method 6 were made during each test.

The Goksoyr-Ross Controlled Condensate (G/R) Method. This is a desirable method because of its simplicity and clean separation of particulate matter, SO_2 and H_2SO_4 (SO_3). This procedure is based on the separation of H_2SO_4(SO_3) from SO_2 by cooling the gas stream below the dew point of H_2SO_4 but above the H_2O dew point. Figure 6-5 illustrates schematically the G/R test system.

Particulate matter is first removed from exhaust gas stream by means of a quartz glass filter placed in the heated glass filter holder. Tissue-quartz filters are recommended because of their proven inertness to H_2SO_4. The filter system is heated by a heating tape so that the gas out temperature of 260°C (500°F) is maintained. This temperature is imperative to ensure that none of the H_2SO_4 will condense in the filter holder or on the filter.

The condensation coil where the H_2SO_4 is collected is cooled by water which is maintained at 60°C (140°F) by a heater/recirculator. This temperature is adequate to reduce the exhaust gas to below the dew point of H_2SO_4.

Three impingers are shown in Figure 6-5. The first impinger is filled with 3% H_2O_2 to absorb SO_2. The second impinger is to remove carryover moisture and the third contains a thermometer to measure the exhaust gas temperature to the dry gas meter and pump. The sampling rate is 2.3 lpm (0.08 CFM).

For both SO_2 and H_2SO_4 determination, the analytical procedure is identical. The H_2SO_4 sample is washed from the back part of the filter holder and the coil using distilled water. The sample from the first impinger which is assumed to be absorbed and reacted SO_2 in the form of H_2SO_4 is recovered with distilled water washing. The amount of H_2SO_4 is the condensate from the coil and from the H_2O_2 impinger is measured by H+ titration. Bromphenol Blue is used with NaOH as the titrant.

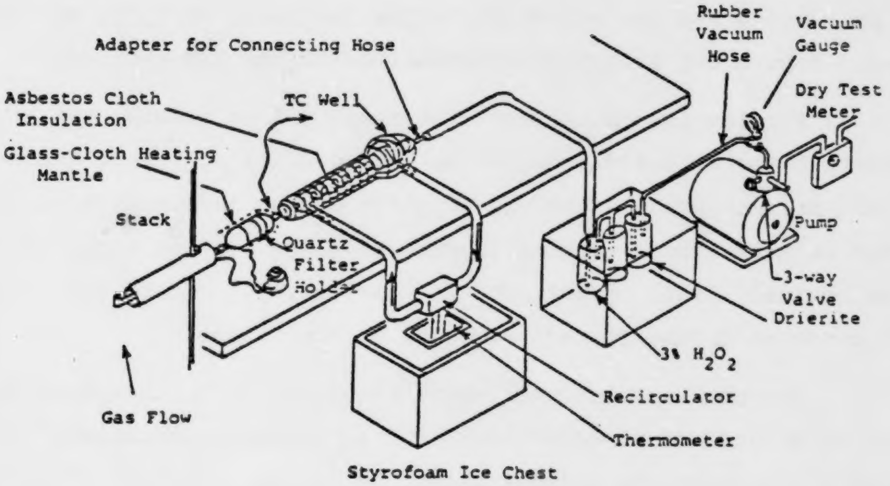

Adapter for Connecting Hose
Asbestos Cloth Insulation
TC Well
Glass-Cloth Heating Mantle
Stack
Quartz Filter Holder
Gas Flow
Rubber Vacuum Hose
Vacuum Gauge
Dry Test Meter
Pump
3-way Valve
Drierite
3% H_2O_2
Recirculator
Thermometer
Styrofoam Ice Chest

Figure 6-5. Schematic of Goksoyr-Ross Controlled Condensation System (CCS).

6.2 PARTICULATE MEASUREMENT AND PROCEDURE

Particulate samples were taken at the same sample ports as the gaseous emission samples using a Joy Manufacturing Company portable effluent sampler (Figure 6-6). This system, which meets the EPA design specifications for Test Method 5, Determination of Particulate Emissions from Stationary Sources (Federal Register, Volume 36, No. 27, page 24888, December 23, 1971), was used to perform both the initial velocity traverse and the particulate sample collection. Dry particulates are collected in a heated case using first a cyclone to separate particles larger than approximately five micrometers, and a 100 mm glass fiber filter for retention of particles down to 0.3 micrometers. Condensible particulates are collected in a train of four Greenburg-Smith impingers in an ice water bath. The control unit includes a total gas meter and thermocouple indicator. A pitot tube system is provided for setting sample flows to obtain isokinetic sampling conditions.

All peripheral equipment is carried in the instrument van. This includes a scale (accurate to ±0.1 mg), hot plate, drying oven (212°F), high temperature oven, desiccator, and related glassware. A particulate analysis laboratory is set up in the vicinity of the boiler in a vibration-free area. Here filters are prepared, tare weighed and weighed again after particulate collection. Also, probe washes are evaporated and weighed in the lab.

6.3 PARTICLE SIZE DISTRIBUTION MEASUREMENT AND PROCEDURE

Particle size distribution of the flyash was measured using several methods. These include the Brink Cascade Impactor, SASS cyclones, and the Bahco Classifier.

Brink. The Brink cascade impactor is an in-situ particle sizing device which separates the particles into six size classifications.

The sampling procedure is straight forward. First, the gas velocity at the sample point is determined using a calibrated S-type pitot tube. For this purpose a hand held particulate probe, inclined manometer, thermocouple and indicator are used. Second, a nozzle size is selected which will maintain isokinetic flow rates within the recommended .02-.07 ft^3/min rate at stack conditions.

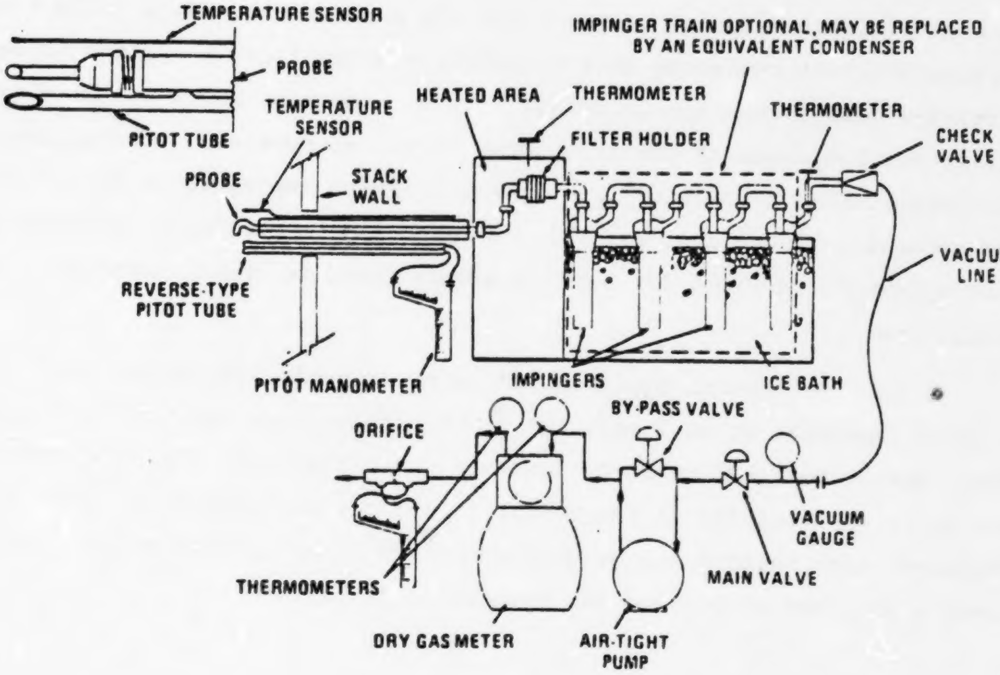

TEMPERATURE SENSOR
PROBE
PITOT TUBE
IMPINGER TRAIN OPTIONAL, MAY BE REPLACED BY AN EQUIVALENT CONDENSER
HEATED AREA
THERMOMETER
TEMPERATURE SENSOR
FILTER HOLDER
THERMOMETER
CHECK VALVE
PROBE
STACK WALL
VACUUM LINE
REVERSE-TYPE PITOT TUBE
PITOT MANOMETER
IMPINGERS
ICE BATH
BY-PASS VALVE
ORIFICE
VACUUM GAUGE
MAIN VALVE
THERMOMETERS
DRY GAS METER
AIR-TIGHT PUMP

Figure 6-6. EPA Method 5 Particulate Sampling Train

Having selected a nozzle and determined the required flow rate for isokinetics, the operating pressure drop across the impactor is determined from a calibration curve. This pressure drop is corrected for temperature, pressure and molecular weight of the gas to be sampled.

A sample is drawn at the predetermined ΔP for a time period which is dictated by mass loading and size distribution. To minimize weighing errors, it is desirable to collect several milligrams on each stage. However, to minimize reentrainment, a rule of thumb is that no stage should be loaded above 10 mg. A schematic of the Brink sampling train is shown in Figure 6-7.

Bahco. The Bahco classifier is described in ASME Power Test Code 28. It is an accepted particle sizing method in the power industry and is often used in specifying mechanical dust collector guarantees. Most Bahco samples are collected by cyclone separation; thus, particles below the cut point of the cyclone are lost. The Bahco samples in these tests were obtained from the cyclone in the EPA Method 5 particulate train. These samples are spatially representative because they are taken from a 24-point sample matrix. However, that portion of the sample below about seven micrometers is lost to the filter. The percentage of the sample lost to the filter is noted in this report. Bahco test data are presented in combination with sieve analysis of the same sample.

SASS. The Source Assessment Sampling System (SASS) was not designed principally as a particle sizing device, but it does include three calibrated cyclones which were used as such. The SASS train was used as a single point, isokinetic sampler like the Brink cascade impactor. However, the SASS train is a high volume sampler allowing the use of .25 to 1.0 inch nozzles as opposed to the typical .08 inch nozzle used on the Brink. The cut points of the three cyclones were 10, 3 and 1 micrometers at Test Sites A, B and C. At the remaining sites, the cut points were 18.5, 5.9 and 1.4 micrometers.

6.4 COAL SAMPLING AND ANALYSIS PROCEDURE

Coal samples were taken during each particulate and SASS test. The samples were processed and analyzed for both size consistency and chemical composition. The samples were taken as close to the furnace as possible in order to obtain samples representative of the coal fired during testing. Samples were

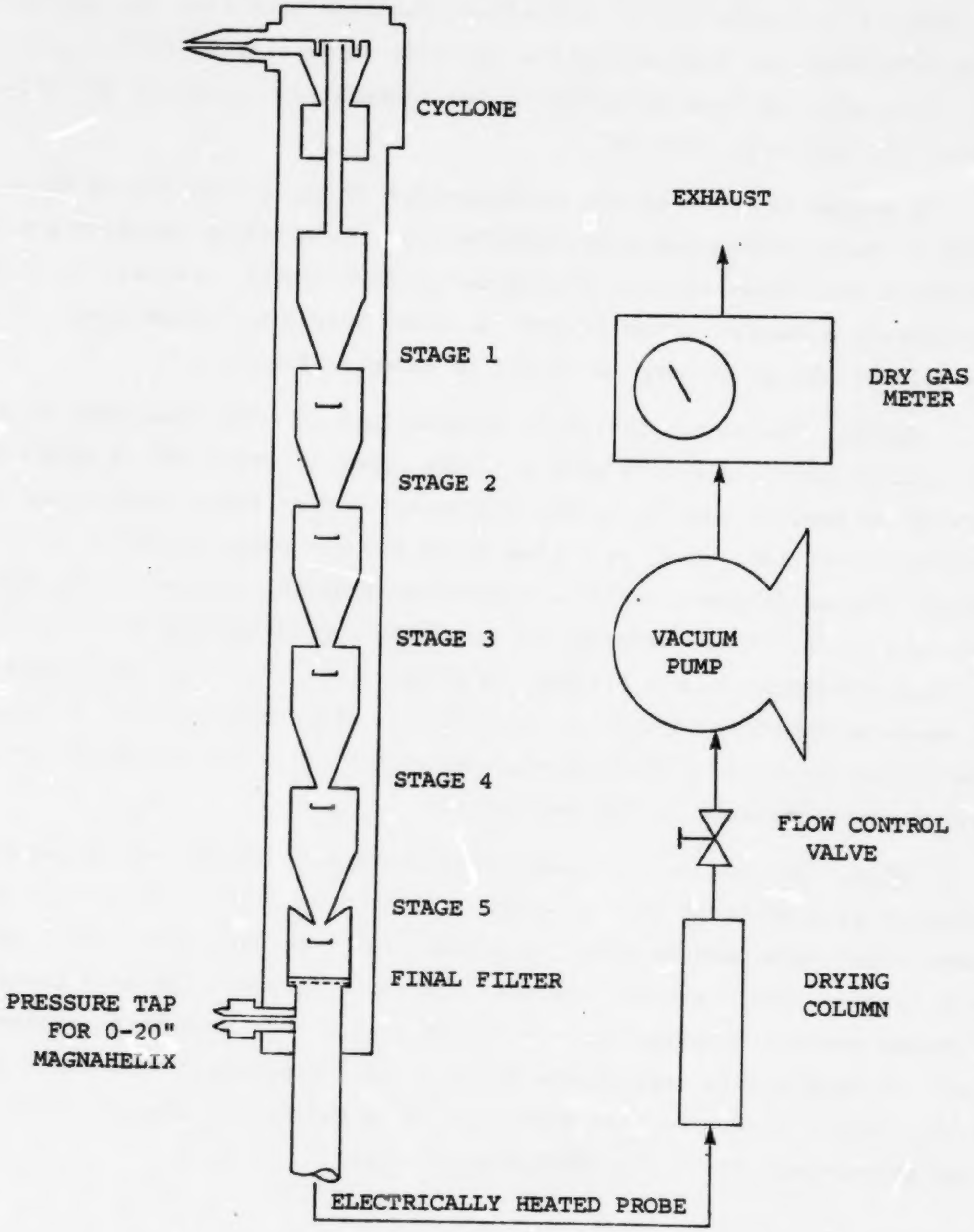

CYCLONE
EXHAUST
STAGE 1
DRY GAS METER
STAGE 2
STAGE 3
VACUUM PUMP
STAGE 4
FLOW CONTROL VALVE
STAGE 5
FINAL FILTER
DRYING COLUMN
PRESSURE TAP FOR 0-20" MAGNAHELIX
ELECTRICALLY HEATED PROBE

Figure 6-7. Brink Cascade Impactor Sampling Train Schematic

taken from the coal scales or weigh lorries at sites with coal weighing devices, while at sites without them, samples were taken from ports installed directly above the feeders.

The sampling procedure was as follows. At the start of testing one increment of sample was collected. This was repeated twice an hour during the test (three to five hours duration) so that a 6 to 10 increment sample is obtained. The total sample is then riffled using a Gilson Model SP-2 Porta Splitter until two representative twenty pound samples are obtained.

The sample to be used for sieve analysis was air dried overnight. Drying of the coal is necessary for good separation of fines. If the coal is wet, fines cling to the larger pieces of coal and to each other. Once dry, the coal was sized using a six tray Gilson Model PS-3 Porta Screen. Screen sizes used were 1", 1/2", 1/4", #8 and #16 mesh. Screen area per tray is 14"x14". The coal in each tray was weighed on a triple beam balance to the nearest 0.1 gram.

The coal sample to be used for chemical analysis was reduced to 2-3 pounds by further riffling and sealed in a plastic bag. All coal samples were sent to Commercial Testing and Engineering Company, South Holland, Illinois. Each sample associated with a particulate loading or particle sizing test was given a proximate analysis. In addition, composite samples consisting of one increment of coal for each test for each coal type receive ultimate analysis, ash fusion temperature, mineral analysis, Hardgrove grindability and free swelling index measurements.

6.5 ASH COLLECTION AND ANALYSIS FOR COMBUSTIBLES

The combustible content of flyash was determined in the field by KVB in accordance with ASTM D3173, "Moisture in the Analysis Sample of Coal and Coke" and ASTM D3174, "Ash in the Analysis Sample of Coal and Coke." The flyash sample was collected by the EPA Method 5 particulate sample train while sampling for particulates.

The cyclone catch is placed in a desiccated and tare-weighed ceramic crucible. The crucible with sample is heated in an oven at 230°F to remove its moisture. It is then desiccated to room temperature and weighed. The crucible with sample is then placed in an electric muffle furnace maintained at a temperature of 1400°F until ignition is complete and the sample has reached a constant weight. It is cooled in a desiccator over desiccant and weighed. Combustible content is calculated as the percent weight loss of the sample based on its post 230°F weight.

Bottom ash samples were collected in several increments from the grate during testing or from the ash pit after testing was completed. These samples were mixed, quartered, and sent to Commercial Testing and Engineering Company for combustible determination.

Multiclone ash samples were taken from ports near the base of the multiclone hopper. This sample, approximately two quarts in size, was sent to Commercial Testing and Engineering Company for combustible determination.

6.6 BOILER EFFICIENCY EVALUATION

Boiler efficiency was calculated using the ASME Test Form for Abbreviated Efficiency Test, Revised, September, 1965. The general approach to efficiency evaluation is based on the assessment of combustion losses. These losses can be grouped into three major categories: stack gas losses, combustible losses, and radiation losses. The first two groups of losses are measured directly. The third is estimated from the ABMA Standard Radiation Loss Chart.

Unlike the ASME test in which combustible losses are lumped into one category, combustible losses were calculated and reported separately for combustibles in the bottom ash and combustibles in the flyash leaving the boiler.

6.7 TRACE SPECIES MEASUREMENT

The EPA (IERL-RTP) has developed the Source Assessment Sampling System (SASS) train for the collection of particulate and volatile matter in addition to gaseous samples. The "catch" from the SASS train is analyzed for polynuclear aromatic hydrocarbons (PAH) and inorganic trace elements.

More information can be found on the SASS equipment, test procedures, and the test results in a separate final report that deals with the SASS testing portion of this program only.

7.0 TEST EQUIPMENT AND PROCEDURES FOR SITES L1 THROUGH L7

This section presents details of the test equipment and sampling procedures that were used to obtain accurate and reliable data at Test Sites L1 through L7.

7.1 MASS EMISSION MEASUREMENTS AND PROCEDURES

Particulate mass samples were taken at the sampling ports using a RAC STAKSAMPLER (Figure 7-1). This system meets the EPA design specifications for Test Method 5, Determination of Particulate Emissions from Stationary Sources (Federal Register, Volume 36, No. 27, page 24888, December 23, 1971). Both the initial velocity and temperature traverse and the particulate sample collection were obtained using this device. Method 5 was followed in setting up and conducting all particulate emission tests.

This method calls for the probe to be attached to a cyclone collector and a filter holder; four impingers, connected in series, follow the filter holder. The first, third and fourth are the modified Greenburg-Smith type while the second is a standard Greenburg-Smith. The control unit is equipped with a pump, a dry gas meter, orifice meter, and two manometers. Temperatures were measured using both dial thermometers and chromel-alumel thermocouples. The pitot tube, the dry gas meter, and the orifice meter were calibrated prior to each series of tests in accordance with the procedures outlined in EPA bulleting No. APTD-0576 (Maintenance, Calibration, and Operation of Isokinetic Sampling Equipment by J. J. Rom).

Particle matter is collected by the cyclone and filter in a case heated to 120°C; the water vapor in the gas stream and the condensible particles condense out in the impinger train which is in an ice bath. The percent moisture in the stack gas is calculated from the increased water volume. Millipore filters are used to separate the insoluble condensibles from the impinger water and the soluble fraction is measured by driving off the water and weighing the residue.

The molecular weight of the stack gas was determined by withdrawing a sample from the gas stream and storing it in a teflon bag. The analysis was per-

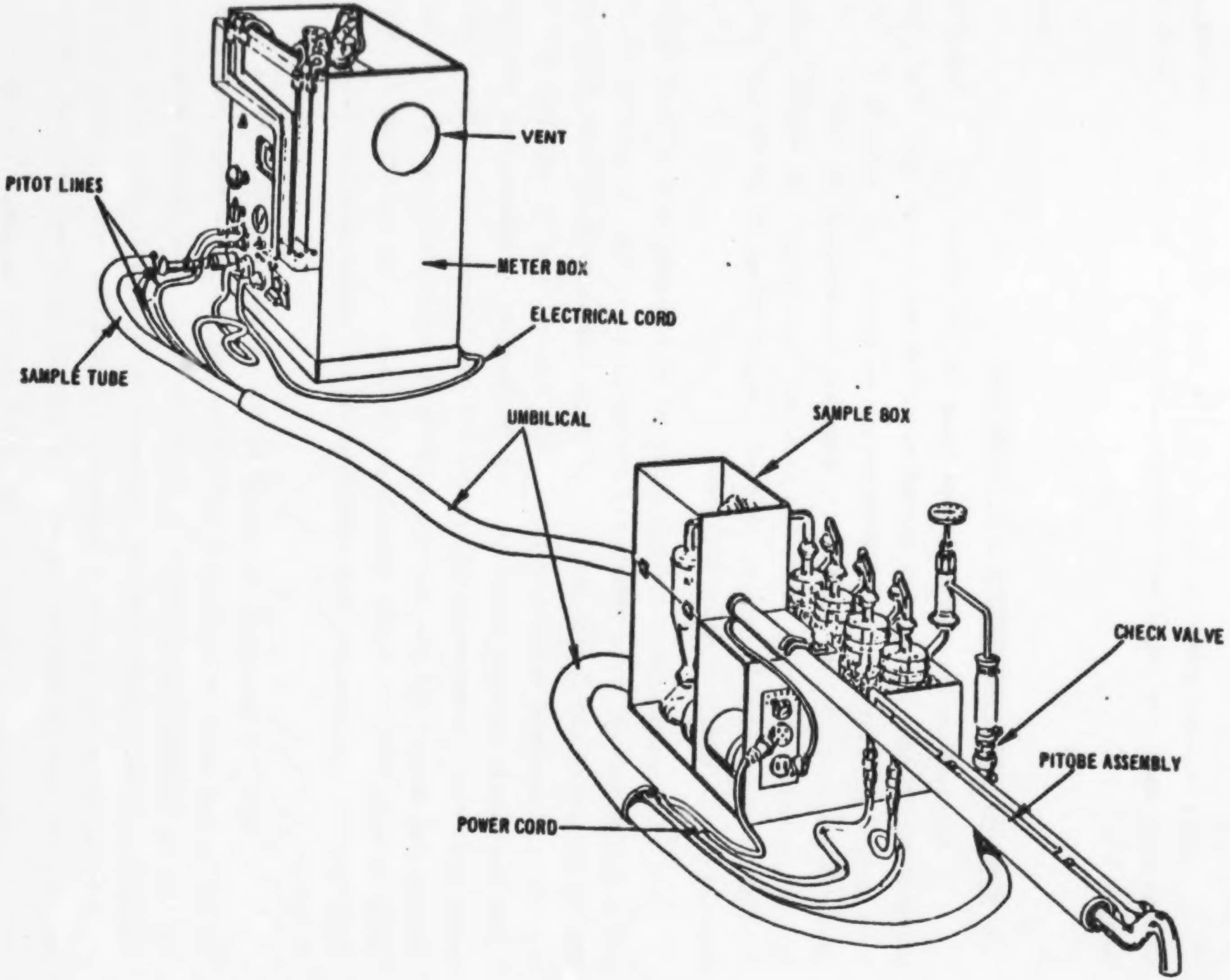

VENT
PITOT LINES
METER BOX
ELECTRICAL CORD
SAMPLE TUBE
UMBILICAL
SAMPLE BOX
CHECK VALVE
PITOBE ASSEMBLY
POWER CORD

Figure 7-1. RAC Staksampler

KVB4-15900-554

formed on site using a standard orsat and checked in the laboratory using infrared analysis for CO and CO_2 and by the use of a micro-fuel cell (Teledyne Instrument) for O_2.

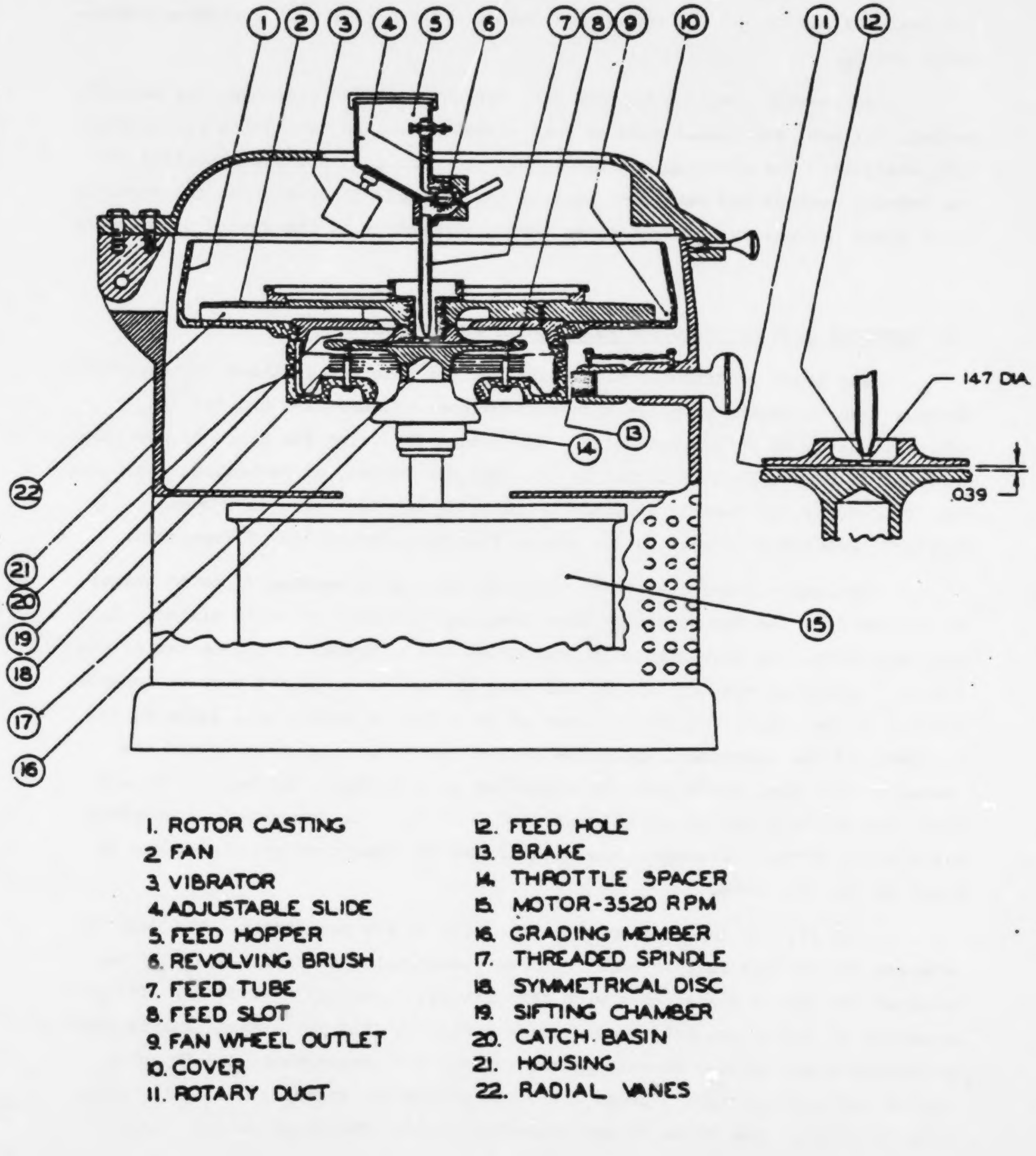
An on-site sampling van was used for sample train clean-up; all particle matter, filters, and liquid samples were stored in sealed containers for laboratory analysis. The clean-up and laboratory procedures were those specified in the Federal methods and were performed in the particle laboratory at the Pennsylvania State University. Calculations were performed using the Method 5 equations.

7.2 PARTICLE SIZE DISTRIBUTION MEASUREMENT AND PROCEDURE

The Bahco centrifugal classifier and the Anderson in-stack impactor are devices used to obtain particle size information. Figures 7-2 and 7-3 are schematic diagrams of the two units. The method for using the Bahco is described in Power Test Code 28 distributed by the American Society of Mechanical Engineers; the "Procedures for Cascade Impactor Calibration and Operation in Process Streams" (EPA-600/2-77-004) is the manual that details the use of impactors.

The centrifugal classifier requires that large samples (1 to 50 grams) be removed from the gas stream by some sampling technique prior to sizing. In the laboratory, the dust sample is introduced into a hopper in the center of the device. Particles are fed into an air flow pattern whose spiral current imparts velocities that carry the larger, heavier particles by centrifugal force to the periphery of the instrument while the smaller particles are swept toward the center of the wheel where they are deposited in a chamber. By varying the air flow, the particle matter can be separated into the size fractions. A complete description of the instrument, the method, and the operating principles can be found in the test code.

The cascade impactor operates directly in the gas stream. The Mark III Anderson device used in this work is shown disassembled in Figure 7-3. It is designed for use in gas streams with temperatures up to 815°C (1500°F). The preseparator at the intake end removes large particles ($>10\ \mu m$). Stack gas is drawn in through a nozzle (not shown), passes through the preseparator and impactor cone to the plate section. There are eight plates (or stages), each with holes slightly smaller than those in the preceding plate. The holes in each plate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22
1. ROTOR CASTING
2. FAN
3. VIBRATOR
4. ADJUSTABLE SLIDE
5. FEED HOPPER
6. REVOLVING BRUSH
7. FEED TUBE
8. FEED SLOT
9. FAN WHEEL OUTLET
10. COVER
11. ROTARY DUCT
12. FEED HOLE
13. BRAKE
14. THROTTLE SPACER
15. MOTOR-3520 RPM
16. GRADING MEMBER
17. THREADED SPINDLE
18. SYMMETRICAL DISC
19. SIFTING CHAMBER
20. CATCH BASIN
21. HOUSING
22. RADIAL VANES

Figure 7-2. Bahco Centrifugal Classifier

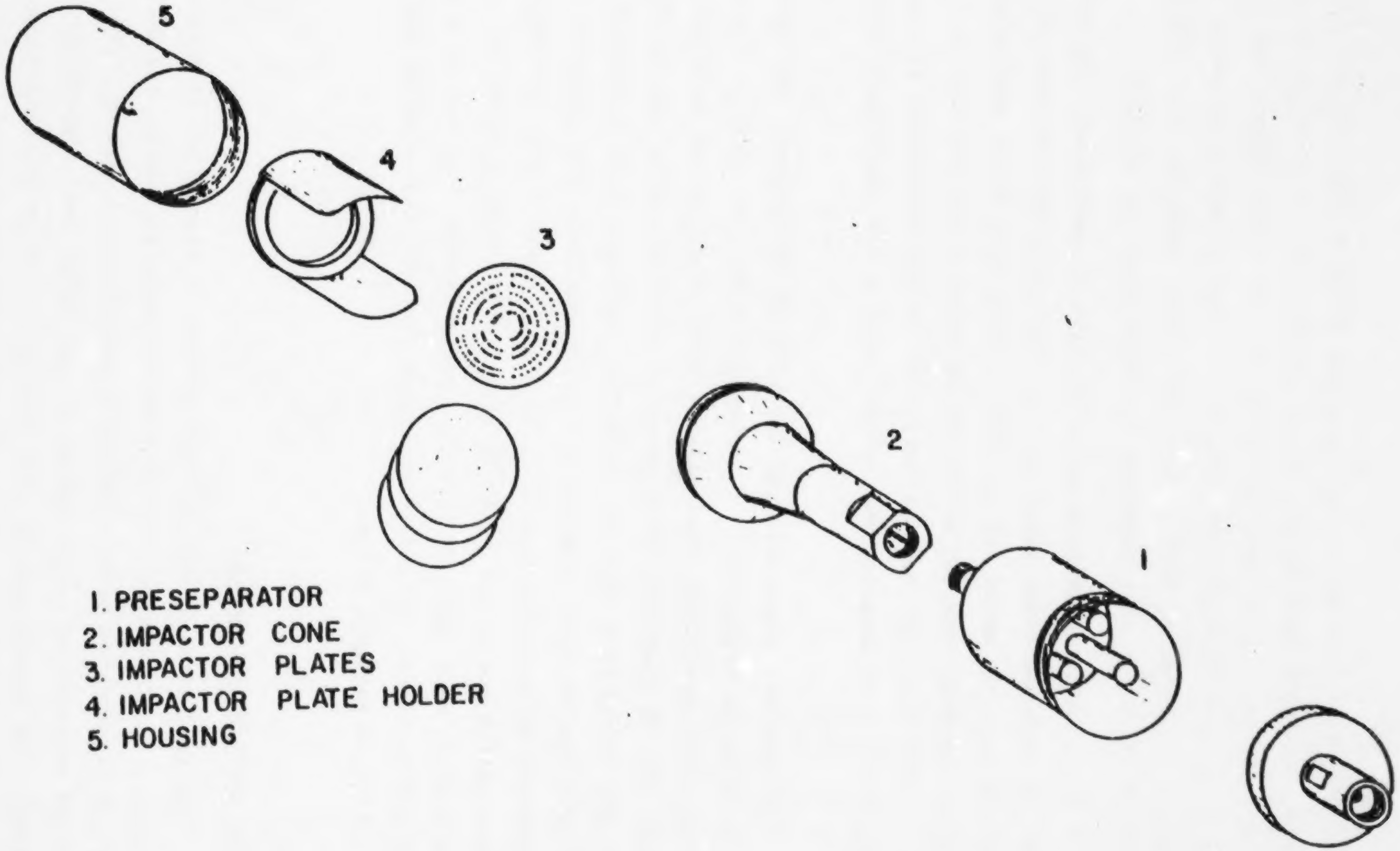
5
4
3
2
1
1. PRESEPARATOR
2. IMPACTOR CONE
3. IMPACTOR PLATES
4. IMPACTOR PLATE HOLDER
5. HOUSING

Figure 7-3. Andersen Mark III In-Stack Impactor

are offset from the plate above and the plate below so that the air passing through a set of holes must impact on the surface of the lower plate and turn sharply in order to pass through the holes in that plate. Since the hole size decreases from plate to plate, the velocity increases and successively smaller particles are collected at each level. The eight stages are followed by an absolute back-up filter that captures the final particle fraction.

A glass fiber collecting media was used on each stage; the media was perforated to keep the holes clear and the collection surface covered. Before and after exposure the media and the final filter were dried over Drierite for 24 hours and weighed. The difference in the weights was the mass in that size fraction. Calibration of the impactor, based on the assumption of spherical particles of 1.0 g/cc density, was accomplished in the laboratory prior to field tests.

The sampling train employed for both the centrifugal and impactor methods is shown in Figure 7-4. A preseparator was used on both trains to collect the large particles; this allowed these particles to be sized by sieving. Power Test Code 28 specifies that the particulate matter be removed directly from the gas stream by a sampling technique. A glass fiber filter was utilized in this case, and multiple samples were taken until about 2 grams of material were collected for particle size analysis in the centrifugal classifier. To strengthen confidence in the particle size distribution obtained by impaction, multiple samples were taken at different points within the duct or stack. A standardized laboratory procedure was instituted for the cleaning and handling of the collected particle matter.

7.3 COAL SAMPLING AND ANALYSIS

The coal storage and handling systems at Test Sites L1 through L7 are very similar. Each receive coal by truck delivery to a receiving hopper, from which it is transported to an in-plant overhead storage bunker. Coal is weighed and transported to individual boiler stoker coal hoppers by a suspended weigh lorry. To obtain coal samples representative of the coal fired during the testing, incremental samples were obtained, using a standard coal shovel, from the weigh lorry discharge at the stoker hopper. The frequency of sampling from the weigh lorry load was varied to obtain a minimum 100 pound sample per test.

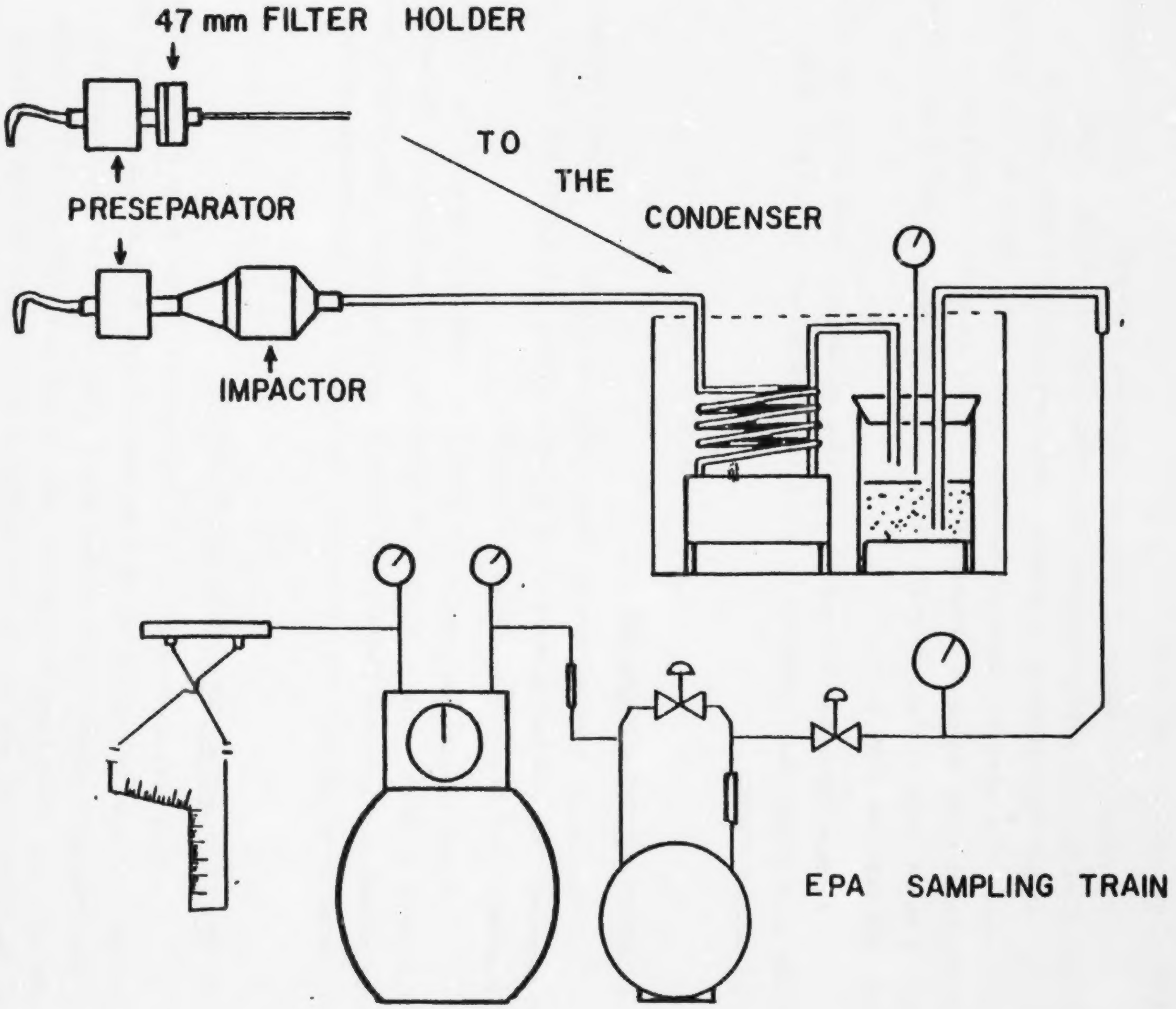
47 mm FILTER HOLDER
PRESEPARATOR
IMPACTOR
TO THE CONDENSER
EPA SAMPLING TRAIN

Figure 7-4. Schematic Diagram of the Sampling Train Used to Collect Particles for the Centrifugal Classifier and Impactor Analysis

As each incremental sample was collected it was placed in a clean metal container with tight fitting cover.

The gross coal sample at each test site was prepared in a sample crushing machine provided with riffle buckets. The final riffling of the gross collection weighed approximately 12 pounds. This was placed in four standard metal sample cans having a capacity of three pounds each. The cans were sealed and delivered to an approved testing laboratory for analysis of moisture, heating value, ash, sulfur, volatile matter, fixed carbon, ash softening temperature, and free swelling index.

At Test Sites L5, L6, and L7 a portion of the uncrushed sample was subjected to a sizing test conducted on a Gilson Porta Screen Model PS-3, with Tyler square screens.

7.4 ASH COLLECTION AND ANALYSIS

Bottom ash samples were collected from the stoker ash pit at completion of testing. The samples were manually crushed, mixed, quartered, and placed in a standard three-pound metal sample container.

Flyash samples were collected from a port near the base of the mechanical collectors on those sites equipped with mechanical dust collectors. The samples were placed in a standard three-pound metal sample container. All samples were delivered to an approved test laboratory for analysis of combustible content.

7.5 BOILER OPERATING PERFORMANCE AND EFFICIENCY

Boiler efficiency testing was not included in the scope of Test Sites L1 through L7. However, operating data recorded every one-half hour provides information necessary to evaluate steaming rates, heat release rates, excess air (oxygen), and combustion efficiency. Coal scales, instruments, and controls at the seven sites are checked and calibrated by the manufacturer's service engineer at regular intervals. Special test equipment, other than an orsat for boiler outlet gas analysis, was not provided.

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APPENDIX A

CONVERSION FACTORS

ENGLISH AND METRIC UNITS TO SI UNITS

To Convert From	To	Multiply By
in	cm	2.540
in^2	cm^2	6.452
ft	m	0.3048
ft^2	m^2	0.09290
ft^3	m^3	0.02832
lb	Kg	0.4536
lb/hr	Mg/s	0.1260
$lb/10^6Btu$	ng/J	430
g/Mcal	ng/J	239
Btu	J	1054
Btu/lb	J/kg	2324
Btu/hr	W	0.2929
J/sec	W	1.000
J/hr	W	3600
Btu/ft/hr	W/m	0.9609
Btu/ft/hr	J/hr/m	3459
$Btu/ft^2/hr$	W/m^2	3.152
$Btu/ft^2/hr$	$J/hr/m^2$	11349
$Btu/ft^3/hr$	W/m^3	10.34
$Btu/ft^3/hr$	$J/hr/m^3$	37234
psia	Pa	6895
"H_2O	Pa	249.1
Rankine	Celsius	C = 5/9R-273
Fahrenheit	Celsius	C = 5/9(F-32)
Celsius	Kelvin	K = C+273
Rankine	Kelvin	K = 5/9R

APPROXIMATE CONVERSION FACTORS FOR A TYPICAL COAL FUEL

ppm @ 3% O_2 (SOx as SO_2)	ng/J ($lb/10^6Btu$)	0.851 (1.98×10^{-3})
ppm @ 3% O_2 (NOx as NO_2)	ng/J ($lb/10^6Btu$)	0.611 (1.42×10^{-3})
ppm @ 3% O_2 (CO)	ng/J ($lb/10^6Btu$)	0.372 (8.65×10^{-4})
ppm @ 3% O_2 (CH_4)	ng/J ($lb/10^6Btu$)	0.213 (4.95×10^{-4})
g/Kg of Fuel	ng/J ($lb/10^6Btu$)	4300 (10)

APPENDIX B

CONVERSION FACTORS

SI UNITS TO ENGLISH AND METRIC UNITS

To Convert From	To	Multiply By
cm	in	0.3937
cm^2	in^2	0.1550
m	ft	3.281
m^2	ft^2	10.764
m^3	ft^3	35.315
Kg	lb	2.205
Mg/s	lb/hr	7.937
ng/J	$lb/10^6Btu$	0.00233
ng/J	g/Mcal	0.00418
J	Btu	0.000948
J/kg	Btu/lb	0.000430
J/hr/m	Btu/ft/hr	0.000289
$J/hr/m^2$	$Btu/ft^2/hr$	0.0000881
$J/hr/m^3$	$Btu/ft^3/hr$	0.0000269
W	Btu/hr	3.414
W	J/hr	0.000278
W/m	Btu/ft/hr	1.041
W/m^2	$Btu/ft^2/hr$	0.317
W/m^3	$Btu/ft^3/hr$	0.0967
Pa	psia	0.000145
Pa	"H_2O	0.004014
Kelvin	Fahrenheit	F = 1.8K-460
Celsius	Fahrenheit	F = 1.8C+32
Fahrenheit	Rankine	R = F+460
Kelvin	Rankine	R = 1.8K

APPROXIMATE CONVERSION FACTORS FOR A TYPICAL COAL FUEL

ng/J	ppm @ 3% O_2 (SOx as SO_2)	1.18
ng/J	ppm @ 3% O_2 (NOx as NO_2)	1.64
ng/J	ppm @ 3% O_2 (CO)	2.69
ng/J	ppm @ 3% O_2 (CH_4)	4.69
ng/J	g/kg of fuel	0.000233

APPENDIX C

SI PREFIXES

Multiplication Factor	Prefix	SI Symbol
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto*	h
10^{1}	deka*	da
10^{-1}	deci*	d
10^{-2}	centi*	c
10^{-3}	milli	m
10^{-6}	micro	µ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

*Not recommended but occasionally used

APPENDIX D

EMISSION UNITS CONVERSION FACTORS FOR TYPICAL COAL FUEL (HV = 13,320 BTU/LB)

To Obtain \ Multiply By		% Weight in Fuel		lbs/10^6Btu		grams/10^6Cal		PPM (Dry @ 3% O_2)		Grains/SCF. (Dry @ 12% CO_2)	
		S	N	SO_2	NO_2	SO_2	NO_2	SOx	NOx	SO_2	NO_2
% Weight In Fuel	S	1		0.666		0.370		13.2×10^{-4}		1.48	
	N				0.405		0.225		5.76×10^{-4}		.903
lbs/10^6Btu	SO_2	1.50		1		(.556)		19.8×10^{-4}		(2.23)	
	NO_2		2.47				(.556)		14.2×10^{-4}		(2.23)
grams/10^6Cal	SO_2	2.70		(1.8)		1		35.6×10^{-4}		(4.01)	
	NO_2		4.44		(1.8)				25.6×10^{-4}		(4.01)
PPM (Dry @ 3% O_2)	SOx	758		505		281		1		1127	
	NOx		1736		704		391				1566
Grains/SCF (Dry @ 12% CO_2)	SO_2	.676		(.448)		(.249)		6.87×10^{-4}		1	
	NO_2		1.11		(.448)		(.249)		6.39×10^{-4}		

NOTE: 1. Values in parenthesis can be used for all flue gas constituents such as oxides of carbon, oxides of nitrogen, oxides of sulfur, hydrocarbons, particulates, etc.
2. Standard reference temperature of 530°R was used.

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APPENDIX E
ORDERING INFORMATION FOR SITE REPORTS

The individual test site reports referenced in this report may be obtained at no charge, if available, from EPA's Center for Environmental Research Information (CERI). It is only necessary to include the EPA report number given in the following table. When CERI's supply of reports is exhausted, paper or microfiche copies may be obtained through the National Technical Information Service (NTIS). When ordering through NTIS, use the NTIS report number found in the following table. Request a copy of the latest price code schedule to translate the NTIS price codes.

CERI: ORD Publications
U.S. EPA
26 West St. Clair
Cincinnati, OH 45268
Telephone: (513)684-7562

NTIS: 5285 Port Royal Road
Springfield, VA 22161

Telephone: (800)336-4700
or (703)487-4700

Test Site	EPA Report No.	NTIS No.	NTIS Price Code Paper Copy	NTIS Price Code Microfiche
A	EPA-600/7-78-136a	PB285172	A06	A01
A sup*	EPA-600/7-78-136b	PB293731	A13	A01
B	EPA-600/7-79-041a	PB295535	A06	A01
B sup	EPA-600/7-79-041b	PB295544	A16	A01
C	EPA-600/7-79-130a	PB80-119324	A07	A01
C sup	EPA-600/7-79-130b	PB80-119340	A19	A01
D	EPA-600/7-79-237a	PB80-144991	A06	A01
D sup	EPA-600/7-79-237b	PB81-175465	A11	A01
E	EPA-600/7-80-064a	PB80-181266	A06	A01
E sup	EPA-600/7-80-064b	PB80-212921	A12	A01
F	EPA-600/7-80-065a	PB80-183023	A06	A01
F sup	EPA-600/7-80-065b	NA**	NA	NA
G	EPA-600/7-80-082a	PB80-187271	A06	A01
G sup	EPA-600/7-80-082b	PB80-187289	A12	A01
H	EPA-600/7-80-112a	PB80-212947	A05	A01
H sup	EPA-600/7-80-112b	PB80-212954	A06	A01
I	EPA-600/7-80-136a	PB80-212822	A05	A01
I sup	EPA-600/7-80-136b	PB80-212962	A06	A01
J	EPA-600/7-80-137a	PB80-219744	A05	A01
J sup	EPA-600/7-80-137b	PB80-212970	A07	A01
K	EPA-600/7-80-138a	PB80-220817	A05	A01
K sup	EPA-600/7-80-138b	PB80-212988	A11	A01
L1-L7	EPA-600/7-81-020a	PB81-196628	A04	A01
L1-L7 sup	EPA-600/7-81-020b	NA	NA	NA

* sup - Data supplement to the report. This is a compilation of raw data sheets and is useful only to the researcher who needs to examine the data in greater detail than that provided in the main report.

** NA - Not available at the time of publication but expected to be available soon.